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THE CALCULATION OF BOILER EFFICIENCIES

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THE CALCULATION OF BOILER EFFICIENCIES

by

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PREFACE

This work was prompted by a letter from the Bureau of Ships, Navy Department, suggesting that a thesis be undertaken on the subject of the calculation of boiler efficiencies, using the Naval Boiler and Turbine Laboratory Long Form as a basis of the discussion. This form has been in general use at the Laboratory for a number of years, and provides a useful tool in the testing and decision as to whether a boiler is acceptable for the Naval service. Therefore, an investigation as to its nature and content, with a view of determining the propriety of the many calculations involved, was deemed worthwhile.

This work was begun in January, 1948, and was completed in May, 1948. I am particularly indebted to Senior Professor Paul J. Kiefer, Professor Dennis Kavanaugh, and Associate Professor Harold M. Wright, all of the U. S. Naval Postgraduate School, for their helpful advice and suggestions in the preparation of this thesis.

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INTRODUCTION

The determination of boiler efficiencies by the Navy or any other organization is very important if the most is to be gotten for the dollar spent for boilers. High boiler efficiency means, for the Navy, greater economy and higher cruising radius, both important for the fighting ships of any country, but especially important for ours, surrounded as we are by water, with the two largest oceans of the world on both sides.

While the method to be discussed here in the determination of boiler efficiency could be employed for any steam generator, the viewpoint of the Navy will be primarily considered. This stems from the fact that this thesis was suggested by the Bureau of Ships, Boiler Division, and it was intended that the standard "Long Form" be used as a basis for the discussion. It was suggested that the effect on efficiency of feedwater temperature, hydrogen in fuel oil, excess air, use of higher or lower heat value of the fuel in calculations, free moisture in fuel, and moisture in the air be treated here and in addition several other aspects of the Long Form have been investigated.

Boiler efficiency is the ratio of the total heat energy absorbed by the generated steam, to the total heat content of the fuel being burned. It is usually desirable that boiler units be of relatively high efficiency, but care should be exercised to determine whether the anticipated saving in fuel in some particular service justifies the capital investment necessary to obtain it. Boilers for Naval service are usually of the highest efficiency obtainable, other matters being considered, with initial expense playing a minor role.

To get a general idea of what is involved in the determination of boiler efficiencies, it is necessary to realize the following; operation of a steam generating unit involves the process of (a) converting potential energy of fuel into heat energy, and (b), transferring this heat energy to a medium (steam) which may be applied to useful purposes. In practice certain characteristic losses of energy occur. The summation of these losses in terms of percent of original available energy in the fuel, are represented by the difference between the percent efficiency and 100 percent. Unavoidable losses result from the necessity of discharging products of combustion at a temperature above that of the temperature of the fuel and of the air for combustion, and from hydrogen and moisture in the fuel. Avoidable losses, which can be controlled to a certain extent, result from excess air that is heated to the temperature of the exit gases; from moisture accompanying such excess air; from unconsumed solid combustibles in ash and refuse; from unconsumed gaseous combustibles in exit gases; and from radiation that might occur from the boiler.

As said before, the efficiency of a boiler is the ratio of the heat absorbed per pound of fuel fired, as measured by the heat given to the steam, to the heat of complete combustion of one pound of fuel. The Naval Boiler and Turbine Laboratory has excellent facilities for measurement of various temperatures, weights, pressures, composition of fuel and gases, that are so necessary if the final results of a boiler efficiency analysis are to be worthwhile. It is doubtful if there is any other facility in the United States, including the boiler manufacturers, that goes to more painstaking care to obtain accurate and complete results. As will be seen from an examination of the Long Form (Figure 1), many of the results and items noted and computed have little or no relation to the actual calculation of the final efficiency. However, they serve as a guide to designers, and contribute to a more complete knowledge of the boiler, besides being standards of comparison between equipment offered to the Navy by different manufacturers.

The Long Form is a printed form of some 150 items, some measured, and some calculated, all aimed at the last space on the forms; "Final Overall Efficiency". It might be said here that although the term "Short Form" is frequently heard, there is no such form in use at present. It was an abbreviated form, which was considered of insufficient scope, and thus abandoned many years ago.

CHAPTER I

THE LONG FORM

It will be well at this point to examine the Long Form in more detail. Many of the constants used proved to be tedious and in some cases difficult to derive exactly as shown, but there is no doubt that the use of these constants expedite the work of calculators considerably.

General Data

Items 1 to 6, inclusive. — Contain boiler heating surface and volume statistics.

Item 1—Generating Heating Surface, in square feet. Generating heating surfaces consist of all boiler tubes that generate steam, that is, act as upcomers. On boilers of the Iowa type for instance, these surfaces include the saturated bank, the water screen, and the side wall.

Item 2—Superheater Heating Surface, in square feet. The superheating surface consists of tubes through which the steam (taken from the drum externally) passes and receives its superheat.

Item 3—Economizer Heating Surface, in square feet. The economizer heating surface consists of tubes above the generating tubes over which the gases of combustion pass, heating the feed water.

Item 4—Total Boiler Heating Surface, in square feet. This item is a summation of items 1, 2, and 3.

Item 5—Air Heater Heating Surface, in square feet. Present types of Naval boilers do not use air heaters, experimental types (Steamotive) excepted. These tubes are always nearest the gas exit.

Item 6—Total Furnace Volume, in cubic feet. The furnace volume is here split into two parts, the saturated furnace and the superheating furnace.

Item 7—Type of Registers. The present types in use are:

(a) Todd air encased.

(b) Carolina.

(c) B and W High Capacity (Iowa).

(d) B and W Cuyama.

(e) Peabody.

(f) Bureau of Eng. Conical.

The last three types are found on old ships.

Item 8—Opening of Register Doors. This item refers to the number of notches the register vanes are open.

Item 9—Position of Burner Barrels. Here is recorded the amount the barrels are withdrawn from their fully-in position.

Item 10—Types of Sprayers. The types are usually indicated by the number of slots, the size of the whirling chamber, etc.

Item 11--Number and Size of Sprayers. Navy sprayer plates are designated by number, such as 2009; the first two digits (20) indicate the size of the drill used for drilling the orifice. The third and fourth digits, with a decimal point placed between them, is termed the "ratio", and indicates the quotient obtained by dividing the sum of the cross-sectional areas of the slots by the cross-sectional area of the orifice.

Item 12--Burners in Use. This item shows the location of the burners, by number on the saturated side, and by letter on the superheater side.

Item 12A--Full Power Equivalent Evaporation. Every boiler is rated on a basis of a given amount of equivalent steam to be generated at its full power condition. Equivalent evaporation = (actual evaporation x factor of evaporation). Factor of evaporation = (H-h)/970.3, where H is the enthalpy of one pound of steam, and h is the enthalpy of one pound of feedwater.

Fuel Particulars

Items 13 to 19--These values represent the chemical composition of the fuel, and are obtained by an ultimate analysis.

Item 20--Heat Value by Calorimeter, in BTU/lb. At the Boiler Laboratory, higher heating values are used in calculations.

Item 20A--Increase in heat value at fuel temperature over that at temperature of air at boiler casing inlet, in BTU/lb. The expression used to obtain this value is

0.46(Item 52-Item 50)

or 0.46(Oil temp.- air inlet temp.)

Where 0.46 is the specific heat of the oil(for ranges of density of 0.95 to 1.0, and from 70 to 180 F)

Item 20B--Increase in Heat Value at Constant Pressure over that at Constant Volume. This item supposedly takes into account the higher heating value obtained by burning the fuel in the furnace at constant pressure over that obtained by burning it in the bomb calorimeter at constant volume. A constant value of 25 BTU per pound is considered correct for any fuel oil likely to be encountered in the testing of boilers at the Boiler Laboratory.

Item 20C—Total Sensible Heat, in BTU/Lb. This is the summation of items 20, 20A, and 20B.

Summarized Test Data

Item 21—Avg. Carbon Dioxide, as a percentage. This is obtained by Orsat, above the economizer.

Item 22--Avg. Oxygen, expressed as percentage. Also obtained by Orsat, above the economizer.

Item 23--Avg. Carbon Monoxide, expressed as a percentage. This is obtained in a like manner.

Item 24—Avg. Nitrogen, expressed as a percentage. This value is obtained by subtracting the sum of the three preceding items from 100.

Item 25—Avg. Steam Drum Pressure in psia inside the steam drum is obtained from gage reading.

Item 26—Avg. Steam Drum Outlet Pressure in psia is taken by gage at the point indicated.

Item 27—Avg. S.H. Inlet Pressure, in psia, is taken by gage at the Superheater inlet.

Item 28—Avg. S.H. Outlet Pressure, in psia, is taken by gage, at the Superheater outlet.

Item 29—Avg. Pressure Before Main Stop, in psia, by gage, as indicated.

Item 30--Avg. Pressure After Main Stop, in psia, by gage, as indicated.

Item 30A--Avg. Water Pressure Before Economizer, in psia, taken by gage at the economizer inlet.

Item 30B--Avg. Water Pressure After Economizer, in psia, taken by gage after the economizer outlet.

Item 31--Average Atmospheric Pressure, by barometer, taken in the pump room.

Item 32--Avg. Air Pressure at Boiler Casing Inlet, in inches of water, is measured by manometer at the air ducts.

Item 33--Avg. Air Pressure at Burners, in inches of water, is taken by manometer before the burners at the double front.

Item 34--Avg. Pressure in Furnace, in inches of water, is measured by manometer at the rear and along the incline of the floor.

Item 35--Avg. Flue Gas Pressure Before Superheater, is measured by manometer in inches of water, but is not taken on most boilers.

Item 36--Avg. Flue Gas Pressure After Superheater, in inches of water, is measured by manometer, but not on most boilers.

Item 37--Avg. Flue Gas Pressure Before Economizer or Air Heater, is measured by manometer, and expressed in inches of water at the appropriate point.

Item 38--Avg. Flue Gas Pressure After Economizer or Air Heater, is taken in the same manner as Item 37, at the appropriate point.

Item 39--Avg. Pressure in Breeching, in inches of water, is not applicable, except in certain types of boilers.

Item 40--Avg. Pressure at Base of Stack. This is the same as Item 38 for most Naval boilers.

Item 41--Avg. Calorimeter Temperature, in degrees F., is taken by thermometer (mercury), at the calorimeter.

Item 42--Avg. Steam Temp. At S.H. Outlet, is taken by a mercury thermometer in the steam line at the superheater outlet.

Item 43--Avg. Steam Temp. After Main Stop, is taken as above at the indicated location.

Item 44--Avg. Temperature Feed Water at Feed Stop, is taken as above at the economizer inlet.

Item 45--Avg. Temperature Feed Water Leaving Economizer, is taken as above at the economizer outlet.

Item 46--Avg. Temperature Gases Leaving G.H.S. is taken by thermocouple at eight points, between the saturated G.H.S. and the economizer.

Item 47--Avg. Temperature Gases Leaving Boiler, in degrees F., is taken by thermocouple at eight points above the economizer.

Item 48--Avg. Dry Bulb Temperature is taken by thermometer on the air gallery before the air duct.

Item 49--Avg. Wet Bulb Temperature is taken by the same instrument and in the same location as was Item 48.

Item 50--Avg. Temperature of Air Entering Boiler Casing Inlet. This item is taken by a resistance thermometer at the air ducts.

Item 50A--Avg. Air Temperature After Air Heater. This item is not used, as at present no Naval boilers are equipped with air heaters.

Item 51--Avg. Air Temperature at Burners. This temperature is measured in degrees F., as above, by thermocouple.

Item 52--Avg. Oil Temperature at Burners. Measured in degrees F., by mercury thermometer.

Item 53--Average Oil Pressure at Burners, in psi, is measured by gage.

Item 54--Total Oil Burned, in pounds. This item is measured by scales located before the oil pump.

Item 55--Total Water Evaporated, in pounds. The water is measured on scales located before the water pump.

Item 56--Duration of the Run. Run times are chosen with consideration to the steadiness of the data, i.e., a constant rate of oil and water and a minimum of fluctuation of temperatures and pressures. Water level at the beginning and end of the run must be the same. The longer the run time, the more closely the true boiler conditions can be obtained. For a close approximation of boiler efficiency, at least two hours of steady steaming should be obtained. Guaranteed and official runs are always made for at least four hours to simulate trials on shipboard.

Item 57--Oil Fired per Hour. The total amount of oil is weighed before burning, but in order to find the amount fired in each furnace, it becomes necessary to use the following formula, which is not shown on the Long Form:

$$X = \frac{D}{AB+C} \qquad \text{and } B = \left[\frac{P}{p}\right]^{\frac{1}{2}}$$

Where A is the number of burners on the side of higher pressure.

B is the ratio of the square root of the higher pressure divided by the lower pressure.

C is the number of burners on the side of lowest pressure.

D is the total oil rate.

X is the capacity per burner on the side of the lowest pressure

P is the higher pressure.

p is the lower pressure.

Items 58 to 63--These items are firing rates and self explanatory.

Item 64--Heat in Preheated Air; BTU per hour per Cu. Ft. Furnace Volume.

This item is computed by the equation

$$\text{Item 61(Item 51-100)(0.24 Item 91 + 0.46 Item 92)}$$

which is oil rate (air temp. at burners - standard air temp.) (0.24 x wt. of dry air used per lb. of fuel - 0.46 x wt. of moisture.)

or oil rate x difference from standard air temp. x (heat of dry air - heat of moisture.) , where 0.24 is used as the specific heat of water vapor.

Item 65--Total Heat Release per Hour per Cu. Ft. of Furnace Volume.

This item is a summation of Items 63 and 64.

Item 66--Average Quality of Steam at S.H. Inlet, in percent. The equation used for this determination is

$$100\left[1- \frac{0.475(T-\text{Item 41})}{L}\right]$$

where 0.475 is the specific heat of saturated steam at atmospheric pressure; T is the dry temperature from calorimeter calibration at the drum outlet pressure; Item 41 is the calorimeter temperature; L is the latent heat of vaporization at the drum outlet pressure.

Item 67--Total Steam Generated Per Hour, in pounds per hour, is obtained by dividing the total water evaporated by the duration of the run.

Item 67A--Sat. Steam Generated Per Hour, in pounds per hour, is directly measurable in the Laboratory.

Item 67B--S. H. Steam Generated Per Hour, in pounds per hour, is obtained by subtracting Item 67A from 67.

Item 68--Total Heat absorbed per Lb. of Saturated Steam, in BTU per pound. This becomes simply the heat of saturated steam at drum pressure - the heat of feed water at economizer inlet temperature.

Item 68A--Total Heat absorbed per Lb. of S.H. Steam, in BTU per pound, is obtained by subtracting the heat of the feed water at economizer inlet temperature from the heat of the superheated steam at the superheater outlet temperature and pressure.

Item 69--Heat absorbed by G.H.S. per Lb. of Steam. This becomes heat of saturated steam at drum pressure - heat of water at economizer outlet temperature.

Items 70, 70A, and 70B--These equations convert the actual evaporation into equivalent evaporation by dividing by 970.3 (heat of vaporization at 212° F., and 14.7 psi.)

Items 71 to 80--These items are primarily evaporation rates, and self explanatory. Item 75 is the determination of Boiler Horse Power by use of the constant 34.5, and Item 76 is a calculation to determine the percent of full power of any run, from evaporation data.

Item 81--Saturated Steam Temp. At S.H. Outlet Pressure, in degrees F., is found using Item 28 and the steam tables.

Item 82--Superheat at S.H. Outlet, is obtained by subtraction of saturation temperature from the superheated steam temperature.

Combustion Calculations

Item 83 to 86--These refer to the relative humidity, dew point, and vapor pressure of the air, and are obtained from psychrometric tables.

Item 87--Weight of Dry Air at Boiler Casing Inlet, in pounds per cubic feet. The equation reads as follows:

$$1.3268 \left[\frac{\text{Item 31} - \text{Item 86} + (\text{Item 32} \div 13.5)}{459.6 + \text{Item 48}} \right]$$

$$\text{or } 1.3268 \left[\frac{\text{Barometric press.} - \text{Vapor Pressure} + \text{air duct pressure}}{\text{Absolute temperature}} \right]$$

$$\text{or } 1.3268 \left[\frac{\text{Pressure "Hg}}{\text{Abs. T.}} \right]$$

For $PV = WRT$ and $P = \frac{144\text{"Hg}}{2.036} = 70.7269\text{" Hg}$

$$R = \frac{1544}{\text{Mo.Wt.}}$$

Molecular Weight of Air

Oxygen	20.99%	20.99 x 32.00 = 671.68
Nitrogen	78.06%	78.06 x 28.016 = 2186.93
Argen	0.95%	0.95 x 39.944 = 37.95
		2896.56

Mol. Wt. of Air is 28.9656

$$R = \frac{1544}{28.9656} = 53.305$$

$$\frac{70.7269\ P}{53.305\ T} = \frac{1.3268\ P}{T}$$

Item 87A--Item 87 Based on 100 F. Air Temperature, with a Relative Humidity of 40%.

Item 88--Dry Air Theoretically Required for Combustion of 1 pound of fuel. This equation is given as

$0.3449\left[\frac{C}{3} + H_2 + \frac{S-O_2}{8}\right]$, and is derived as follows

$C + O_2 = CO_2$

$12 + 32 = 44$

$2H_2 + O_2 = 2H_2O$

$4 + 32 = 36$

$S + O_2 = SO_2$

$32 + 32 = 64$ Parts O_2

$\frac{C}{3} = \frac{12}{3} = 4$ $\frac{32}{4} = 8$

$H_2 = 4 = 4$ $\frac{32}{4} = 8$

$\frac{S}{8} = \frac{32}{8} = 4$ $\frac{32}{4} = 8$

Density of O_2 = 1429 @ 0°)
" " Air = 1293 @ 0°) From International Critical Tables Volume I -
O_2 = 20.99% by volume) pages 102 and 393

By wt. $\frac{20.99 \times 1429}{1293} = 23.198\%$

$\frac{100}{23.198} \times 8 = 34.486$ = constant

Dividing by 100, this becomes 0.3449

$\frac{100}{23.198} = 4.31071$ lbs. of air to yield 1 lb. of O_2

There are 8 lbs. of O_2 for each lb. of H_2

$4.31071 \times 8 = 34.486$ lbs. of air for each lb. of H_2,

or, when expressed as a percentage, 0.3449.

Item 89--Weight of Dry Gases Per Lb. of Fuel. This item is expressed by the following equation:

$$\left[\frac{4CO_2 + 700}{3(CO_2 + CO)}\right] \left[\frac{C + S \div 1.835}{100}\right]$$

$$\frac{\text{Lb. of dry gas}}{\text{Lb. of C in fuel}} \qquad \frac{CO_2 + CO + O_2 + N_2}{CO_2 + CO} \qquad \frac{\text{Gas}}{\text{Fuel}}$$

$$\frac{44CO_2 + 28CO + 32O_2 + 28N_2}{44CO_2 + 28CO}$$

But CO_2 is 12/44 carbon and CO is 12/28 carbon;

$$\frac{11CO_2 + 7CO + 8O_2 + 7N_2}{3(CO_2 + CO)}$$

$$N_2 = 100 - CO_2 - CO - O_2$$

$$7N_2 = 700 - 7CO_2 - 7CO - 7O_2$$

$$11CO_2 + 7CO + 8O_2 + (700 - 7CO_2 - 7CO - 7O_2)$$

$$\frac{4CO_2 + O_2 + 700}{3(CO_2 + CO)}$$

One lb. C yields 3.667 lbs. CO_2

" " S " 1.998 " SO_2

Atomic wts.: C = 12.01 O_2 = 32.00 S = 32.064

$$\frac{3.667}{1.998} = 1.8353$$

Therefore, correction for sulfur to wt. of dry gases =

$$\frac{C + \frac{S}{1.8353}}{100}$$

Item 90--Weight of Moisture From Burning Hydrogen. This value is obtained by multiplying Item 15 by 0.0894

$$2H_2 + O_2 \longrightarrow 2H_2O$$

$$2 \times 2.0156 + 32.000 = 36.0312$$

Pound of H_2 per pound of water $= \frac{36.0312}{4.0312} = 8.94$

Item 91--Weight of Dry Air Used Per Pound of Fuel. This item is obtained by subtracting the weight of the oil from that of the dry gases, per pound of fuel, and the weight of the moisture formed from burning hydrogen, per pound of fuel.

Item 92--Weight of Moisture in Air Per Pound of Fuel. This is given by the equation

$$\frac{\text{Item 91 x Item 84}}{\text{Item 87}}$$

or $$\frac{\text{Weight of dry air,(lbs./lb) x moisture in air,(lbs./cu. ft.)}}{\text{Density of air,(lbs./cu. ft.)}}$$

Item 92A--Item 92, Based on 100°F. Air Temperature and Relative Humidity 40%

Item 93--Weight of Total Products of Combustion per Pound of Fuel. Given by equation

Item 89 + Item 90 + Item 92

or Wt. of dry gas + Wt. of moisture from burning H_2 + Wt. of moisture in air

Item 94--Per Cent Excess Air.

$$100\left(\frac{\text{Item 91}}{\text{Item 88}} - 1\right)$$

or $$100\left(\frac{\text{Actual dry air}}{\text{Theoretical dry air}} - 1\right)$$

Item 95--C.F.M. Air Through Blowers In Cubic Feet Per Minute. Expressed by

$$\frac{\text{Item 57}}{60} \times \frac{\text{Item 91}}{\text{Item 87}}$$

or $$\frac{\text{oil fired lbs./hr.}}{\text{60 min./hr.}} \times \frac{\text{dry air used lbs./lb.}}{\text{Density of air lbs./ft.}^3}$$

Item 95A--Air Horsepower is given by the following expression

$$\frac{\frac{h \times 62.4}{12} \times C.F.M.}{33{,}000} = 0.000157576 \times h \times C.F.M.$$

h = Air pressure in inches of water, Item 32

C.F.M. = Cubic feet per minute of air, Item 95 at 100° F., this becomes

$$\frac{\frac{h \times 62.00}{12} \times C.F.M.}{33{,}000} = 0.000156566 \times h \times C.F.M.$$

Item 97--Per Cent Total Steam Used to Operate Blowers. Expressed by the following equation

$$100 \frac{(\text{Steam required by blowers})}{(\text{Total steam generated})}$$

Item 98--Pounds of Steam Used by Blowers per 1000 Cubic Feet of Air Supplied. This is given by

$$16.667 \frac{(\text{Item 96})}{(\text{Item 95})}$$

or

$$\frac{1000}{60} \frac{(\text{Steam used by blowers})}{(\text{C.F.M. through blowers})}$$

Item 99--Per Cent Total Steam Remaining After Deducting Blower Steam. Simply

100 - Per cent steam required by blowers

Item 100--Lowest Theoretical Stack Temperature. Indicated as below for different types of boilers

a) Boiler with air heater: air inlet temperature.
b) Boiler with economizer: feed water temperature.
c) Boiler without air heater or economizer: Saturation temperature at drum pressure.

Heat Balance

Item 101--Heat Loss: Moisture from H_2 in fuel from temperature air entering boiler casing to lowest theoretical stack temperature.

(1089.0 + 0.46 Item 100 - Item 50) Item 90

The heat lost in stack gas is that:

a) To heat the moisture to saturation temperature
b) To change from water to steam
c) To superheat to stack temperature

The concept here is that a) can be expressed by (212-t), where t is the air temperature at the casing inlet; that b) is the latent heat of evaporation, 970.3; that c) is the heat in the vapor, or 0.46 (T-212), where T is the lowest theoretical stack temperature. The sum of these is (212 - t) + 970.3 + 0.46 (T-212), which when cleared becomes 1084.8 + 0.46T - t. The difference in this expression and the one inside the parentheses above is apparent, and it is proposed that the value 1089.0 be used since 1084.8 was calculated, assuming that atmospheric pressure was involved, which is not the case.

Item 102--Heat Loss: Free moisture in fuel from temperature oil at burners to lowest theoretical stack temperature. All fuel oils will probably contain some moisture, and here the loss of heat required to bring this moisture to lowest theoretical stack temperature is obtained by an equation similar to Item 101:

$$(1089.0 + 0.46\ (\text{Item } 100) - \text{Item } 52)\ \frac{\text{Item } 19}{100}$$

Where Item 19 is the percent of free moisture in the fuel, and Item 52 is the Avg. Oil Temp. at Burners.

Item 103--Heat Loss: Moisture in Theoretical Air from Temperature Air Entering Boiler casing to Lowest Theoretical Stack Temperature, in BTU. Here it is attempted to calculate the third source of heat loss due to moisture, which is the BTU necessary to raise the temperature of the moisture in the entering air to the indicated point. The calculation is performed by making use of the equation

$$\frac{\text{Item 92 x 0.46 (Item 100 - Item 50) Item 88}}{\text{Item 91}}$$

or, Wt. of moisture in air x Sp. heat (Lowest theoretical stack temp. - air inlet temp.) x theor. dry air req'd.

Item 104--Heat Loss: Theoretical Dry Flue Gases from Temperature Air Entering Boiler casing to Lowest Theoretical Stack Temperature, in BTU. This loss, classified as unavoidable also, is calculated by the expression

$$\text{0.25(Item 100 - Item 50) (Item 88 + 1 - Item 90)}$$

or Specific heat of gas x (theoretical stack temperature - air inlet temperature) x (dry air required per pound of fuel + one lb. of fuel - moisture in the gas per pound of fuel)

Item 105--Total Unavoidable Losses, in BTU. This item is the summation of items 101 to 104, inclusive. It must be pointed out that if a boiler is equipped with an air preheater, these losses may be reduced, as stack temperatures approach inlet air temperatures.

Item 106--Heat Loss: Incomplete Combustion of Carbon. If combustion is not complete, and some part of the carbon constituent of the fuel is burned to carbon monoxide instead of carbon dioxide, the loss due to such incomplete combustion is very appreciable. The equation used for such a computation is

$$10160 \left(\frac{CO}{CO_2 + CO} \right) \left(\frac{C}{100} \right)$$

10160 BTU is the difference in the amount of heat evolved in the combustion of one pound of carbon to carbon monoxide and to carbon dioxide.

Item 107--Heat Loss: Excess Air from Temperature Air Entering Boiler Casing to Lowest Theoretical Stack Temperature. For complete combustion there must be excess air, and the loss occasioned by heating this air to the indicated temperature is

$$0.24 \text{ (Item 100 - Item 50) (Item 91 - Item 88)}$$

where 0.24 is taken as the specific heat of dry air.

Item 100 is lowest theoretical stack temperature.

Item 50 is the temp. of the air entering the casing inlet.

Item 91 is the weight of dry air per lb. of fuel.

Item 88 is dry air theoretically required for 1 lb. of fuel.

Item 108--Heat Loss: Moisture Accompanying Excess Air from Temperature Air Entering Boiler Casing to Lowest Theoretical Stack Temperature. Here is computed the loss resulting from heating the moisture accompanying the excess air from its initial state to the indicated temperature; and the equation for this computation is

$$\frac{\text{Item 103 x Item 94}}{100}$$

where Item 103 is the loss due to moisture in the theoretical amount of air, from heating from boiler casing temperature to the lowest theoretical stack temperature, and Item

94 is the percent of excess air.

Item 109--Heat Loss; Dry Flue Gases from Lowest Theoretical Stack Temperature to Temperature Gases Leaving Boiler, in BTU. This is a loss that becomes greater at higher steaming rates, when the temperature of the exit gases becomes higher, and is given here by the equation

$$0.25 \text{ (Item 47 - Item 100) Item 89}$$

where 0.25 is taken as the specific heat of the gases of combustion; (Item 47 - Item 100) is the indicated temperature difference; and Item 89 is the weight of the dry gases per pound of fuel.

Item 110--Heat Loss: Moisture in Dry Flue Gases from Lowest Theoretical Stack Temperature to Temperature Gases Leaving Boiler. This is a similar item to 104, in that the total weight of the moisture from burning hydrogen plus the moisture in the air per pound of fuel plus the free moisture in the fuel is multiplied by the temperature difference indicated, and the constant 0.46, which is taken as the specific heat of water vapor.

$$0.46 \text{ (Item 47 - Item 100) (Item 90 + Item 92 + } \frac{\text{Item 19}}{100} \text{)}$$

Item 111--Heat Loss: Chargeable to all Absorbing Surfaces, in BTU, is the sum of Item 109 and 110. These losses can be regarded as avoidable and if the unit is equipped with an air heater, Item 105 must be included, for as pointed out, these losses in that particular case are not unavoidable.

Item 112--Heat Absorbed by Total Boiler Heating Surface, in BTU, is found from previous Items listing the amounts of saturated and superheated steam generated per hour, the amount of heat absorbed by each pound of the two types of steam, and the actual rate of evaporation per pound of oil,

or Item 74 $\left(\frac{\text{Item 68 x Item 67A + Item 68A x Item 67B}}{\text{Item 67}} \right)$

Item 113--Heat Loss: Unconsumed H_2 and Hydrocarbons, Radiation, and unaccounted for. This is a loss that cannot be measured directly. Some energy is still unaccounted for after the above items concerning known heat losses are calculated, and there is no other recourse except to list them as unaccounted for. Therefore, the expression used is

Item 20C - (Items 105 + 106 + 107 + 108 + 111 + 112)

where item 20C is the total sensible heat in the fuel oil.

Item 114--Heat Loss: Chargeable to Furnace and Burners. It is considered that the furnace and burners are directly responsible for the losses occurring from incomplete combustion, excess air, and the moisture accompanying it, and Item 113. This Item then is a summation of Items 106, 107, 108, and 113.

Item 115--Heat Loss: Chargeable to all Absorbing Surfaces and Furnace and Burners. The components of this loss have been calculated earlier in the Form, and this then becomes Item 111 + Item 114.

Item 116--Heat Absorbed by G.H.S. per lb. of Fuel, is an item which gives the portion of heat absorbed by the generating heating surface only. Item 69 multiplied by Item 74 will give the desired result, for this becomes the heat absorbed by G.H.S., per pound of steam multiplied by the actual evaporation of steam, per pound of oil.

Item 117--Heat Absorbed by E.H.S. per Lb. of Fuel, is a determination of the above result for the economizers. The equation for this is

$$\text{Item 74}\ (h_1 - h)$$

where Item 74 is the actual evaporation per pound of oil, and h_1 is the enthalpy of the feed water at Item 45, and h the enthalpy of the feed water at Item 44.

Item 118--Heat Absorbed by S.H.S. per Lb. of Fuel parallels Item 116 and Item 117, for the superheaters. It is obtained by subtracting from the total heat absorbed from all the boiler heating surfaces the sum of that absorbed by the saturated side and the economizers.

Item 119--Heat Absorbed by Air from Entrance to Fireroom to Boiler Casing Inlet, per pound of fuel. This is the heat gained by the air and its contained moisture from the indicated reference points, and is determined by

$$(0.24 \times \text{Item 91} + 0.46 \times \text{Item 92})\ (\text{Item 50} - \text{Item 48})$$

0.24 and 0.46 being the specific heats used for dry air and water vapor, respectively.

Item 120--Heat Available for Absorption by Total Boiler Heating Surface is the sum of the heat loss chargeable to all absorbing surfaces, Item 111, plus the heat actually absorbed by the total boiler heating surfaces, Item 112.

Item 121--Heat Available for Absorption by E.H.S., is the same as Item

120 in that this heat is the sum of the heat loss chargeable to all the absorbing surfaces and the heat absorbed by the economizers, per pound of fuel.

Item 122--Heat Available for Absorption by A.H.S. is not calculated, in the absence of an air preheater, but could be done quite easily by adding the heat loss chargeable to all absorbing surfaces and the heat absorbed by air from boiler casing inlet to the burners, per pound of fuel.

Resultant Efficiencies

Item 123--Overall Efficiency of Total Boiler H.S. and Furnace and Burners. This is the total heat absorbed by all the boiler heating surfaces divided by the sensible heat of the oil,

or $\frac{\text{Item 112}}{\text{Item 20C}}$

Item 124--Combined Efficiency of Absorbing Surfaces. This is a ratio of the heat absorbed by the total boiler heating surfaces, to the heat available for absorption by these surfaces, or

$$\frac{\text{Item 112}}{\text{Item 120}}$$

Item 125--Combined Efficiency of Furnace and Burners. This efficiency expression does not charge the unit with the losses found to be unavoidable, and therefore becomes the ratio

$$\frac{\text{Item 120}}{\text{Item 20C} - \text{Item 105}}$$

or the total heat available for absorption by the boiler heating surfaces, divided by the total sensible heat of the fuel minus the unavoidable losses.

Item 126--Combined Efficiency of Absorbing Surfaces and Furnace and Burners, eliminating unavoidable losses. This formula does not apply to boilers with an air heating surface, but for others, it is quite similar to Item 123, with the exception that the denominator is decreased by the amount of the unavoidable losses.

$$\frac{\text{Item 112}}{\text{Item 20C} - \text{Item 105}}$$

Item 127--Efficiency of G.H.S., S.H.S., and Furnace and Burners, without E.H.S. or A.H.S. This expression becomes

$$\frac{\text{Item 112} - \text{Item 117}}{\text{Item 20C}}$$, which is seen to be similar

to Item 123, except that the heat absorbed by the feed water in the economizers is subtracted from that absorbed by the total boiler heating surface.

Item 128--Efficiency of G.H.S. and S.H.S. The total amount of heat absorbed by the two surfaces is divided by the total sensible heat of the fuel to give the desired efficiency.

$$\frac{\text{Item 116} + \text{Item 118}}{\text{Item 120}}$$

Item 129--Efficiency of E.H.S., shows the actual efficiency of the economizers. As the actual amount of heat absorbed by the E.H.S. per pound of fuel is known, and also the total amount of heat available for absorption by the E.H.S., the division of the former by the latter will indicate the efficiency. This is

$$\frac{\text{Item 117}}{\text{Item 121}}$$

Item 130--Efficiency of A.H.S. This efficiency can be computed by dividing the amount of heat absorbed by the air from the boiler casing inlet, Item 119A, by the heat available for absorption by the air heaters, providing that this unit is installed.

Item 131--Fireroom Efficiency. This item expresses the boiler efficiency when taking into account the steam used by the forced draft blowers. This steam is furnished by the boiler and the quantity available for the engines is reduced by the amount used in these units. This efficiency, therefore, is lower than when the boiler is credited with the total steam generated, as in Item 123. The equation used is

$$97030 \left(\frac{\text{Item } 72 - \frac{\text{Item } 96}{\text{Item } 57}}{\text{Item } 20C} \right)$$

Pertinent Pressure Losses

Items 132 to 140A--These items are entitled "Pertinent Pressure Losses", and express the drop, in inches of water and in pounds per square inch, through the boiler casing and heating surfaces. These items do not directly concern the efficiency of a boiler, but may well indicate to the designer how efficiency may be bettered. This follows from the fact that the velocity of the gases, and thus the ability to transfer heat by convection, is directly related to pressure drops throughout the furnace.

Corrections To Be Added Algebraically To Overall Efficiencies

Items 141 to 147--These corrections, ordinarily of very small magnitudes, correct Item 123, the "Overall Boiler Efficiency". Item 141 corrects for any variation in hydrogen content from 10.5% in the fuel. Item 142 corrects air temperature to 100° F. Item 143 applies a correction to convert relative humidity to 40%. Item 144 corrects for free moisture in the fuel, using .1%, by weight, as a standard. These items, added to Item 123, give the "Corrected Overall Efficiency."

An examination of the Long Form shows a very complete tabulation of pertinent operating conditions, and calculations of rates, losses, absorption data, and final efficiencies. In a study of the calculation of boiler efficiencies by use of this form, it is soon realized that the general procedure is one that is almost universally followed by engineers, and as will be shown, is similar in nature, but in more detail than the procedure recommended by the A.S.M.E. Boiler Test Code. Many of the items, such as the data given under "General Data", and "Summarized Test Data" cannot be criticized. The same is true in "Fuel Particulars", for most of the items here are from laboratory reports. "Pertinent Pressure Losses" enter into calculations in no manner whatsoever, and methods of measurement are straightforward. "Corrections To Be Added Algebraically to Overall Efficiencies" reduce overall efficiencies to a common basis, to enable comparisons to be more readily made between different tests.

Certain items throughout the form are worthy of investigation and comment, however, and this is also true of certain techniques of measurement.

After the testing of each new boiler submitted to the Navy, the Naval Boiler and Turbine Laboratory issues a complete report upon its performance. The Bureau of Ships, Navy Department, made available for this study a copy of Report No. 2440, of the Fletcher Type Boiler. This boiler is considered to be typical of those installed in most combatant naval vessels at the present time, as far as type is concerned. It is a left hand air-encased, single uptake, divided furnace, superheat control, express boiler with convective type superheater and extended-surface economizer. It is designed to produce 122,500 pounds of steam per hour at computed full power (105,500 pounds of steam per hour at 850° F. and 565 psi for the main engines, plus 17,000 pounds of saturated steam taken from the steam drum for auxiliaries). I have used the actual test results, entered on the Long Form, in many places in the following pages, and it is evident that any results from calculations involving these test figures, apply only to the Fletcher report.

CHAPTER II

SPECIFIC HEATS OF GASES

In the calculation of the heat loss due to heating the dry flue gases from the lowest theoretical stack temperature to the temperature of the gases leaving the boiler (Item 109), a value of 0.25 is used for the specific heat. It would be well to look at this value more closely to see if it is appropriate.

In the range of temperature of gases encountered in stack temperatures with modern boilers, it is not necessary to take into account the variation of specific heat with the temperature, for in this relatively short range these values are effectively constant. Therefore the following equation for ascertaining equivalent specific heats of gas mixtures is appropriate.

$$Cm = \frac{Mx}{Mm} cx + \frac{My}{Mm} cy + \frac{Mz}{Mm} cz$$

where cx, cy, and cz are individual specific heats of the constituents, and Mx, My, and Mz are the masses of each constituent, and Mm the total mass of the mixture.

Looking at a typical gas analysis obtained with a Fletcher boiler on test, the volumetic analysis was as follows:

CO_2 - 13.9%
O_2 - 3 %
N_2 - 83.1%

This volumetic analysis must be reduced to an analysis by weight, as follows, recalling that

$$\frac{Mx}{Mm} = \frac{\frac{Vx}{Rx}}{\frac{Vx}{Rx} + \frac{Vy}{Ry} + \frac{Vz}{Rz}}$$

R of CO_2 = 35.13
R of O_2 = 48.31
R of N_2 = 55.16

Thus

$$\frac{Mx}{Mn} = \frac{\frac{13.9}{35.13}}{\frac{13.9}{35.13} + \frac{3}{48.31} + \frac{83.1}{55.16}} = 20.15\%\ CO_2$$

Similarly, for O_2, $\frac{My}{Mn} = 3.16\%$

For nitrogen, $\frac{Mz}{Mn} = 76.7\%$

Calculation of equivalent specific heat proceeds as follows:

$$C_{mix} = (.2015)(.208) + (.0316)(.218) + (.767)(.248) = .2388$$

This value, checked against several other sums shown in the Fletcher Boiler report, varied in the third decimal place, indicating that 0.24 would probably be a better value to use in Item 109.

It must be admitted that this is a trifling correction, but in the interest of attaining utmost accuracy, a value of 0.24 would be better. It is believed that the gas analysis shown above is a typical one, and that in modern boilers likely to be under test at the Naval Boiler and Turbine Laboratory, analysis would not vary much. In case they did, it is quite easy to calculate a more suitable value of specific heat from average data.

The triviality of the difference incurred in using 0.24 rather than 0.25 can be shown in analyzing the results of Report No. 2440, Item 109.

Maximum difference in BTU, per pound of fuel, is in overload conditions. Here instead of 1243.8 BTU/lb., the loss becomes 1205 BTU per pound, or a difference of 38.8 BTU per pound of oil burned. Differences become much less at lower rates of combustion.

CHAPTER III

EXCESS AIR

Excess air in a furnace is necessary to assure the complete combustion of the fuel, but unfortunately it has the effect of cooling the furnace interior and the temperature of the gases of combustion, thus lowering the overall boiler efficiency. It is necessary therefore to strike a balance, attempting to attain only that percentage of excess air that will assure complete combustion, and no more, if possible. If there is a deficit of air with respect to ideal requirements, hydrogen will tend to acquire its full quota of oxygen, but some portion of the carbon will pass out entirely unburned, or will burn incompletely to CO.

In the test of a full size boiler, such as those designed for Naval ships, it is not feasible to meter the air coming in to the furnace. Instead recourse is made to an analysis of the products of combustion to determine their composition and thus the percentage of air over the ideal requirements. At the Naval Boiler and Turbine Lab, an Orsat apparatus is used for this determination.

Usually the products of combustion contain both CO and O_2 in addition to N_2 and CO_2 and H_2O. Using the Orsat analyzer, a volumetric analysis of products of combustion on a dry or water-vapor-free basis can be made in the following manner. A sample of the gases are collected over water at room temperature in a burette, and its volume measured at atmospheric pressure. It is then exposed to a potassium hydroxide solution that absorbs the CO_2. After the loss in volume is measured, the sample is then passed through alkaline pyrogallate to absorb the O_2, and finally through acid cuprous chloride to absorb the CO, the decrease in volume being determined each time. If the temperature remains constant, the partial pressure exerted by the saturated water vapor remains constant and the volumetric analysis so determined is on a dry or moisture-free basis.

One point to note is that if SO_2 is present, it is absorbed with the CO_2, and this will cause an error if much sulphur is present in the fuel. Also care must be exercised to pass the gas through the solutions in the correct order, for the pyrogallate chloride solution will remove both O_2 and CO.

If coal with a low volatile or hydrocarbon content is being burned, the combustion analysis based on an Orsat analysis is quite reliable. However, when a high volatile coal or petroleum fuel is incompletely burned, the heating value loss by the unburned hydrogen and hydrocarbons in the stack or exhaust gases may, and very often does, greatly exceed that due to carbon monoxide.

In modern Naval boilers design has progressed to such a point that rarely, under proper operating procedure, does incomplete combustion occur, and in tests, CO does not appear. Also if CO is not present, there is little chance of unburned hydrogen or hydrocarbons, such as methane, to be present. Therefore, the Orsat apparatus, if used with proper technique, will provide the necessary in formation to determine accurately the actual composition of the combustion products.

There is evidence that either improper sampling or improper operating technique is used by the Naval Boiler and Turbine Laboratory, however. If a fuel of given composition is burned, the percentage of hydrogen to carbon can be expressed by the expression

$$\frac{N_2 \times \frac{.2099}{.7901} \times 2 - (CO_2 \times 2 + CO) \times 2 \times 1.008}{(CO_2 + CO) \times 12.01} \quad \text{or}$$

$$\frac{N_2 - 3.77\,(CO_2 + O_2 + 0.5CO)}{CO_2 + CO} \times .089$$, as given in Kiefer, Stuart, and Kinney.

Considering the results of Report No. 2440 on the Fletcher boiler Run "C", CO_2 was .14, O_2 was .021, and N_2 was .839. There was no CO detected. The above expression becomes

$$\frac{.839 - 3.77\,(.14 + .021)}{.14} \times .089 \doteq .1476$$

The actual ratio of hydrogen to carbon, from chemical analysis is $\frac{11.06}{86.88} =$ .127

Considering Run "G"

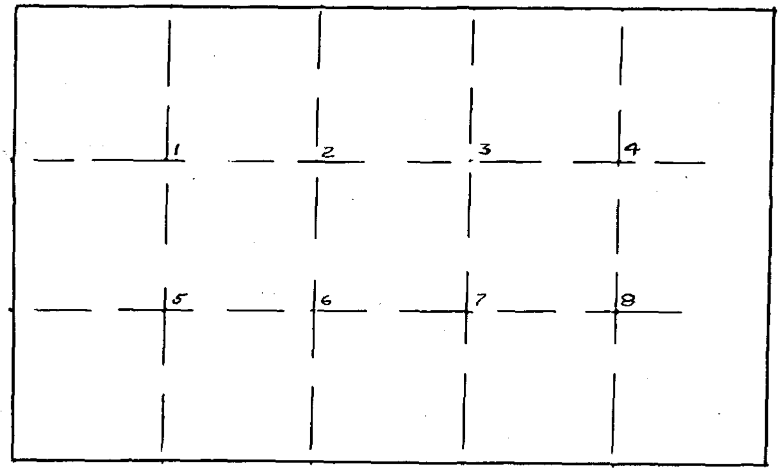
CO_2	13.7%
O_2	2.9%
N_2	83.8%

$$\frac{.838 - 3.77\,(.137 + .029)}{.137} \times .089 = .1382$$

Actual ratio of hydrogen to carbon is .1253

These runs are representative of the error noted in all the tests of Report No. 2440, and indicate either improper Orsat operation, or improper sampling. I believe that the latter is occurring.

The method of taking Orsat analysis at the Naval Boiler and Turbine Laboratory is as follows. The section of the furnace above the economizers is divided into five equal sections along the long axis, and into three equal sections along the short axis, as below:



At each point numbered from 1 to 8 above, is located a stainless steel tube the end of which is cup shaped, and turned downwards. Samples of the gases are drawn off from each of the numbered points, and are analyzed in succession. Each analysis takes approximately 12 minutes, thus a complete round of analysis takes 96 minutes. After the gas from point number 8 is analyzed, the cycle is started again and continued during the duration of the test. At the end of the run, which is usually of four hours duration, all readings are averaged, and the average taken as the most representative value throughout the run. These are the readings entered on the Long Form. It might be mentioned that when steady conditions are upset, such as might occur when burners are changed, the readings are discontinued until the run has steadied again.

Results of one set of eight readings may vary considerably. For example, the CO_2 at No. 1 might be 10.7%; that at 4, 12.2%; and that at 7, 13.2%. This is due to stratification of the gases as they come up the furnace, and the nature of this stratification is next to impossible to determine exactly. Also small holes might be present in furnace joints, and entering air might contribute to one corner of the boiler having radically different gas composition.

It can be seen that the more sampling points that are taken, the more chances of getting an average, or representative sample, are likely. However, engineers at the Boiler Laboratory feel that by the use of eight points, they can get a sufficiently accurate sample.

The present method of location of sampling tubes can be improved, I feel, by using the following method. Divide both the long and short sides of the stack into three equal parts, and in the middle of the nine rectangles thus formed, place a sampling tube. Thus tubes are closer to the sides and corners of the stack, where variations and stratification occurs most frequently, and a better average can be gotten. This means that nine tubes instead of eight are used.

As noted before, in Report No. 2440, a comparison between test analysis of stack gases and calculated values by the above equations indicate that errors are in the order of two or three percent. Actually, it is doubtful if this order of error could be decreased to any great extent by the addition of more sampling tubes. So it must be concluded that present methods of Orsat analysis are reasonably exact at the Boiler Laboratory, if results of Report No. 2440 are representative. Continuous sampling during a test with nine tubes instead of eight should give slightly better results.

To insure the best possible results, assuming that operation of the Orsat equipment was errorless, would require making the uptake cylindrical and installing a fan in the uptake to mix the gases thoroughly. Then the necessity of sampling at many points could be avoided. In view of the necessity of changing the many test installations at the Laboratory, it is doubtful if this suggestion would receive much consideration.

CHAPTER IV

QUALITY OF STEAM

Item 66 of the Long Form is titled "Avg. Quality of Steam at S.H. Inlet", and this percentage is given by the equation

$$100 \left(1 - \frac{.475\ (T - \text{Item } 41)}{L} \right)$$

where 0.475 is the specific heat of saturated steam at atmospheric pressure; T is the dry saturated temperature from calorimetric calibration at the drum outlet pressure; Item 41 is the calorimeter temperature, and L is the latent heat of vaporization at drum outlet pressure. This is an empirical formula, and can lead to errors of considerable magnitude.

In general, when a wet vapor passes through a throttling process, enthalpy of the vapor does not change, and also some degree of superheat will exist at the lower vapor pressure. In the superheat region the pressure and temperature will suffice to determine the state and the enthalpy of the fluid, and both these quantities are measurable. By reason of these facts, the use of a throttling calorimeter is permitted to find the amount of moisture in the vapor.

The final results can be arrived at in two ways; by an h-s, or Mollier, diagram, or by numerical calculation. Both are simple, and can produce answers of any desired accuracy, providing that in the first case, a large chart is available. In the use of the Mollier diagram, the downstream calorimeter temperature and absolute pressure is located, then a line is traced horizontally to the line representing the upstream pressure. The temperature or the moisture content at the latter intersection represents the condition of the original sample.

Numerically, the quality "x" can be calculated from the equation

$x = (h_2 - h_f)/h_{fg}$, where h_2 is the enthalpy of superheated steam at calorimeter pressure and temperature; h_f the enthalpy of the liquid of the high-pressure steam entering the calorimeter; and h_{fg} the latent heat of vaporization of the high-pressure steam.

Comparison of the method of the Long Form with the latter equation in a few instances will show that a discrepancy in results occurs. For example, in a simple case where steam at 200 psia is throttled to a pressure of 16 psia, with a calorimeter temperature of 260° F, the quality by Item 66 is 93.1%; actually the quality is 97.1%, an error of 4%.

CHAPTER V

BOILER HORSE POWER

Item 75 of the Long Form is entitled "Boiler Horse Power", and this is a most controversial item. The origin of the concept of a "boiler horse power" is very interesting, having its origin some seventy years ago.

To go back a little further, the difficulties in dealing with boiler processes are all concerned with the establishment of some fundamentally sound relations for the capacity of heating surface to absorb heat in terms of the amount of heat developed by the burning of oil in a furnace, when the dimensions are known. After all these years of experience, for boilers have existed in one form or other for over two hundred years, and in spite of much theorizing and thousands of recorded tests, it is not possible today to calculate from any fundamental relations either the amount of steam that will be developed per hour with a given fuel, or the weight of the steam that will be produced per pound of fuel. This can be done from empirical relations, of course, because nothing is simpler than a comparison of the boiler in question, and its fuel, with similar ones for which tests have been made. It must be said, therefore, that there is no generally accepted fundamental theory of steam boiler capacity, but there are some relations between certain important established factors, so a discussion of steam boilers must be almost entirely confined to these relations which cannot yet be grouped together to constitute a general theory of the subject. To say it a little differently, there is no absolute measure of boiler performance, as to capacity, as a basis of comparison to measure the goodness of a boiler, as a boiler; comparisons must, therefore, be between one and another boiler, or one and another service condition.

The term "boiler horsepower" in regards to measurement of boiler capacity first appears in the literature during the period when steam pressures were very low, about 70 pounds gage, and when steam engines were not as economical as they are now, nor as different in type and in steam consumption. At that time it was easier to discuss the average steam consumption of engines than it is now, and the number that departed from the average was not great, this average being about thirty pounds per hour per horse power. Accordingly, a boiler was said to have 100 horsepower capacity when it could make steadily 3000 pounds of steam per hour, and thus was boiler horsepower defined. In time, all sorts of variations appeared; better and worse engines were built, higher steam pressures and boiler feed temperatures were also used, so that no longer did the making of 30 pounds of steam per hour take from the fire the same amount of heat as when boiler pressures were uniformly lower, and feed temperature more constant. Therefore, with these variations in evidence, an adjustment of the boiler horsepower definition became necessary. In America this was done by the A.S.M.E., adopting a double definition which was:

(a) The evaporation of 34.5 pounds of water per hour from and at 212° F;

(b) The absorption by the water between fuel conditions and that leaving the boiler, of 33,305 B.T.U. per hour.

The last definition was most fortunate as it is an absolute unit, and whether it has any relation or not to engine requirements, is a matter of no importance whatsoever. It was believed to be the equivalent of the weight definition and would be, if the latent heat of evaporation at 212° were $\frac{33,305}{34.5} = 965.4$.

Now that the latent heat is known to be higher than 965.4, and the use of superheat is quite general, the heat equivalent of a boiler horsepower is 970.3 x 34.5 = 33,478 B.T.U./hr. With the heat basis as a standard, the weight of water evaporated per hour per boiler horsepower will, of course, vary regularly with the initial water temperature and final steam condition, and a factor of evaporation should be calculated for reduction of weights.

A proper basis for comparing two sets of data for different boilers at equivalent capacities are the figures on evaporation per square foot of heating surface per hour, or better still, the heat absorbed per square foot of heating surface per hour. Thus different boilers may be said to be operating at the same capacity when their heating surface rate of heat absorption are the same, though one may be developing 50 and the other 1000 boiler horsepower.

The use of the factor 34.5 is therefore seen to be outmoded at this time, having an origin which was peculiar to conditions existing long ago. It is gradually disappearing from use, and the deletion from the Long Form would be an excellent step in furthering its complete disappearance from use and the literature. To associate this term "boiler horsepower", with the ordinary mechanical definition of mechanical horsepower, only leads to utmost confusión. Consider the Fletcher type boiler, which when tested at full power delivered 4329 Boiler Horsepower. Four of these boilers in a Destroyer engineering plant should therefore deliver 17,316 horsepower. But rated horsepower of the engines driven by the steam generated from these boilers, is in the vicinity of 60,000 horsepower, and no reconciliation between the two terms "horsepower" is possible.

CHAPTER VI

FREE MOISTURE IN FUEL

Free moisture, at first glance, enters the combustion calculations on the Long Form in three places. In each of these it appears as a heat loss; first, that loss due to the energy that raises the free moisture in the fuel from the original temperature at the burners to the lowest theoretical stack temperature. This is Item 102 of the Form. Second, there is an additional loss due to the necessity of heating the moisture in the flue gases from the lowest theoretical stack temperature to the temperature of the gases leaving the boiler. This is Item 110 of the Form. And last is Item 144, where a final correction to the overall efficiency, previously computed. Here it is assumed that a "standard" fuel will have 0.1% moisture, and if more than this is actually present, a correction is computed to correct the overall efficiency back to a value which would have resulted if a "standard" fuel had been used. This last correction is an arbitrary one, and as such, little can be said about it, but it can be seen that it is quite likely that in actual service, more moisture will be present in any fuel received aboard ship.

An appropriate correction which might be included in the Long Form is one that arises from the fact that in the determination of heating value, no attention is paid to the fact that there is moisture in the fuel. In other words, heating values are expressed in terms of BTU per pound of fuel. However, some of this pound of "fuel" is water, and therefore the calorific value of the oil is higher than is reported. No heat is lost in the calorimetric determination, due to water being present, for it is evaporated and superheated, then condenses, giving up its heat again. For small moisture contents this would be a negligible factor, but in the interest of an exact determination, this factor should be considered.

If a fuel oil contained 0.2% water, and a calorimeteric determination of the heating value showed 18,500 BTU/lb., the correct calorific value of the oil is $\frac{100}{99.8}$ x 18500 or 18560 BTU. Conversely, if a fuel with no water present, or only a trace, shows 18500 BTU/lb., then is contaminated with 0.2% water, a pound of the resulting mixture will have a calorific value of (.998) (18500) of 18460 BTU/lb.

All of the fuels used by the Boiler Laboratory seem to be remarkably free from contamination by moisture, but in the event that the water content of the fuel is large, a correction back to true heating value of the oil alone will be an essential to obtain good results in later calculations.

CHAPTER VII

HEAT LOSS FROM MOISTURE IN FUEL

Item 101 is titled "Heat Loss: Moisture in Fuel from Temperature Air Entering Boiler Casing to Lowest Theoretical Stack Temperature". Calculation of this loss is given by the equation (1089.0 + 0.46 x Item 100 - Item 50) Item 90.

The above will bear close scrutiny. It has been developed in the following manner:

The total heat energy of the moisture at the upper temperature level is

$$(212 - t) + 970.3 + 0.46\ (T - 212)$$

where t is Item 50, or air temperature at the boiler casing inlet; T is the Lowest Theoretical Stack Temperature; 0.46 is the average specific heat of water vapor; and 970.3 is the latent heat of evaporation at 212°F and 14.7 psi. When cleared, the equation becomes 1084.8 + 0.46T - t.

In the original computation, 4.2 BTU's are added to 1084.8 BTU, making a total of 1089 for the first term. This is considered as correcting for the fact that the vapor pressure in lower than atmospheric, actually in the vicinity of one pound.

The corrected equation bears a close resemblance to one given by Barnard, Ellenwood, and Hirshfield in "Heat Power Engineering". According to this text, the enthalpy of superheated steam at pressures under 2 psia, and at temperatures (t_x) between 200 and 600 degrees F can be closely obtained by the empirical equation

$$h_x = 1057 + 0.46\ t_x$$

At low temperatures $h_f = t_f - 32$ (approximately), therefore the loss due to the moisture in the fuel is equal to $W_m(1089 + 0.46\ t_x - t_f)$, where W_m is the moisture in the fuel, per pound; h_f is enthalpy of water at the temperature of the entering fuel; and h_x is the enthalpy of the steam in the exit gas at temperature t_x.

It is of interest to check the accuracy of the empirical equation "$h_x = 1057 + 0.46t_x$", at different temperature levels, comparing the values of enthalpies obtained with actual enthalpies obtained from steam tables. This is done in the following table and in Figure 2.

T	H by table	$1057 + .46t_x$	dH	$1057 + c_pt_x$	dH
120	1114.3	1109.2	- 5.1	1111	- 3.3
200	1150.4	1149	- 1.4	1147.4	- 3.0
300	1195.8	1195	- 0.8	1193.5	- 2.3
400	1241.7	1241	- 0.7	1240.2	- 0.5
500	1288.3	1287	- 1.3	1287	- 1.3
600	1335.7	1333	- 2.7	1243.8	+ 7.1
700	1383.8	1379	- 4.8	1397.2	+ 13.4
800	1432.8	1425	- 7.8	1453	+ 20.2
900	1482.7	1470.5	-12.2	1510.6	+ 27.9
1000	1533.5	1517	-16.5	1570	+ 36.5

It can be seen from Figure 2 that in the range of 200 to 300 degrees the empirical equation as given is very accurate at one pound vapor pressure. Likewise, the corrected empirical equation, using corrected values of specific heats is most accurate in the 400 to 500 degree range. Outside this range, as temperatures increase, the results become more in error.

For example in Run "E" of Test No. 2440, the calculated heat loss by formula would be $1089 + (.46)(1000) - 104 \quad (.99)$ or 1638; a percentage loss in this case of $\frac{(100)(1638)}{18675} = \underline{8.775\%}$, as tabulated.

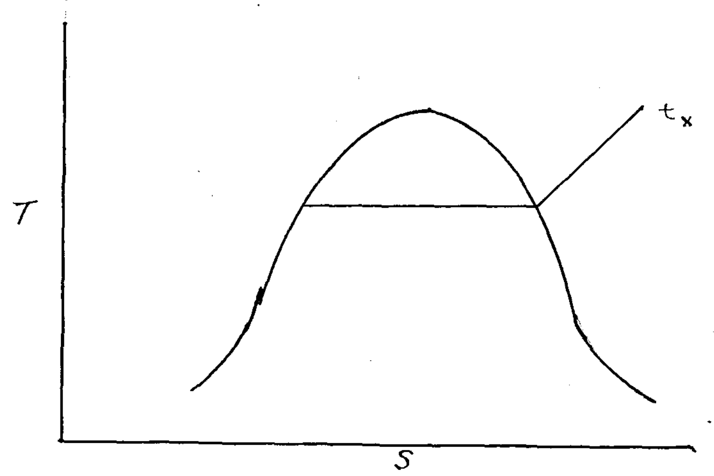
A variation of 36.5BTU, shown above, would mean $\frac{(100)(1674.5)}{18675} = \underline{8.98\%}$ loss, giving a difference between the two of roughly 0.2%. Now this is certainly an extreme case, for it is inconceivable that a present day boiler might be designed so as to have a lowest theoretical stack temperature of 1000°F. Also, if this temperature were 600°F, a possibility if no air preheater or economizer were installed or at extremely high rates of combustion, indicated loss by Item 101 would become

$$1089 + (.46)(600) - 104 \quad (.99) = 1248 = \frac{(1248)(100)}{18675} = 6.68\%$$

Using steam tables, this loss becomes

$(100)\frac{1255}{18675} = 6.72\%$, a variation of .04%, and inconsequential.

After considering the above, it would seem that a more appropriate and exact equation could be formulated to represent this loss. Looking at the process on T-S coordinates, it appears as follows:



The loss is the energy that would be required to re-cool the superheated vapor from the lowest theoretical stack temperature, to saturated water, at the temperature of the air entering the boiler casing. Thus, an appropriate expression is

$[H_{fg}$ + cp(Lowest theoretical stack temperature - entering air temperature)$]$ weight of moisture from burning hydrogen.

Checking this expression against the tabulated results in Report No. 2440 for comparison, the following is obtained:

<u>Run"E"</u> Item 101 = 1086.3 BTU

H_{fg} @ 110° = 1031.6

cp(avg) = .452

(.452) 244.1-104 = <u>108.7</u>
1140.3BTU

1140.3 (0.99) = <u>1130</u> BTU

This indicates a difference of 43.7 BTU, or a variation of 4.08% with the original calculated value. This would mean that the percent heat loss by this method becomes $\frac{1130.0}{18675}$ or 6.05% against 5.82%.

<u>Run "B"</u> Item 101 = 1043.7

H_{fg} @ 106° = 1033.8

cp(avg) = .452

(.452) 245-106 = <u>61.3</u>
1095.1

(1095.1 .95 = 1043 BTU

In this case the two equations give almost identical answers; 1043.7

versus 1043, and no complaint can be made. But for conformity and correctness of results, the use of the expression $\left[H_{fg} + cp\ (t-T)\right]$ weight of moisture is suggested. Realizing that this form is made up for use by calculators, it still remains a simple expression, and any person could be trained to obtain values of H_{fg} from the steam table. Also, average values of cp are easily obtainable, or could be put in chart or curve form for easy interpolation. As in most cases with present day boilers, the values of T and t are not large, nor widely separated and a constant could be devised for use. It would not vary greatly during tests of individual boilers, and thus a very good value of specific heat could be devised.

CHAPTER VIII

STEAM ATOMIZATION

In some types of Naval boilers under consideration for future use in the Fleet, steam is used to atomize the fuel oil. The oil is supplied to the equipment at low pressures and atomization is accomplished by means of a jet of high pressure steam. At present the Long Form has no provision for this operation, and the following additions are suggested.

Under "Fuel Particulars", and after "Heat Value by Calorimeter", include an item "Increase in Heat Value Due to Atomizing Steam, BTU/lb." An expression for this value is "atomizing steam, per pound of oil x enthalpy of atomizing steam, per pound of oil". The total amount of steam going to atomization can be measured by a Bailey type meter, and when this is divided by the amount of oil used during the run, the first part of the expression is obtained. The second part of the expression can be gotten from a knowledge of the pressure and the temperature of the saturated steam at the atomizer, which will give its enthalpy.

The next addition is under the heading "Primary Calculations", probably after Item 64, and is headed "Heat in atomizing steam, BTU/lb. per cubic foot furnace volume". This value is added to Item 63 and 64 to give "Total Heat Release per hour per cubic foot Furnace Volume". Source of this is steam tables, for the state of the atomizing steam is known.

Under "Combustion Calculations", after Item 92, will come an Item entitled "Weight of Atomizing Steam", to be combined with Items 89, 90, and 92 to give the weight of the total products of combustion, per pound of fuel.

Under "Heat Balance", an item is inserted "Heat Loss-Moisture in Atomizing Steam from Air Temperature Entering the Boiler to Theoretical Lowest Stack Temperature". Calculation of this value can be made using the following equation:

H_{fg} + c_p (theoretical lowest stack temperature - entering air temp.), all of the above being multiplied by the weight of the atomizing steam.

H_{fg} must be taken at the inlet air conditions. The result of the above is added to Item 105 to obtain "Total Unavoidable Loss."

The last Item to be included is entitled "Heat Loss: Moisture in Atomizing Steam from Lowest Theoretical Stack Temperature to Temperature to Temperature Gases Leaving Boiler". The specific heat of water vapor multiplied by the difference in the noted temperatures, and by the weight of the atomizing steam, will give the correct result and can be added to Items 109 and 110 to give "Heat Loss: Chargeable to All Absorbing Surfaces".

It might be mentioned that while there are many advantages of using steam for atomization, there is one serious drawback. At present, a sizeable portion (up to 3%) of the steam generated by the boiler is used in the atomization, and represents a relatively large loss of feed water. Some method of reducing this amount must be found before this method can be seriously considered, for the steam used represents a total loss to the cycle, and must be replaced by water made by the evaporators.

CHAPTER IX

FLUE GAS TEMPERATURE

An important item in the investigation of the performance of a boiler is the temperature of the gases leaving the boiler. Also it is one of the most difficult items to measure with any degree of accuracy. Engineers have realized this fact for many years, of course, and have constantly tried to improve methods of measurements. It would be well to set down a few of the considerations involved in the technique of ascertaining these temperatures.

The measurement of the temperature of a gas is subject to errors which do not occur in the case of a solid or liquid. A thermocouple of sufficient length or ordinary design, used with a good indicating instrument, if immersed in a hot liquid, will give the temperature very accurately. Similarly, a thermocouple peened into a surface will give an accurate reading, if certain ordinary precautions are observed. As no heat is lost by the thermocouple, it must reach the temperature of the material very rapidly. On the other hand, a different condition exists for a gas. A thermocouple immersed in a gas receives heat by convection from the gas, but there will be also radiant heat exchange with the chamber walls which it can "see". If the wall surfaces "seen" are at the same temperature as the gas, the thermocouple will read the true temperature of the gas, because no radiant heat exchange will take place. On the other hand, if the containing walls are hotter than the gas, they will radiate heat to the thermocouple which, because of the extra heat received, will read higher than the true gas temperature. If the walls are at a lower temperature they will absorb radiant heat from the thermocouple, and hence the thermocouple will read lower than the true gas temperature. A more important case is that of a modern steam boiler furnace where the combustion gases are often completely surrounded by "cold" water wall surface.

The hourly radiant heat exchange from the thermocouple to the surrounding surface is given by the equation

$$Q = CeA_1 \left[\left(\frac{T_t}{100}\right)^4 - \left(\frac{T_W}{100}\right)^4 \right]$$

The hourly convection heat from the gas to the couple is given by this equation;

$$Q = h_c A_2 \ (T_g - T_t)$$

where Q = hourly heat transferred (BTU/lb)

A_1 = area of the thermocouple surface, in sq. ft.

A_2 = area of the gas film around the thermocouple, in sq. ft.

C = the coefficient of a blackbody (0.1723).

e = the emissivity of the thermocouple surface.

h_c = coefficient of convection heat transfer (BTU/sq.ft.hrF)

T_t = temperature of the thermocouple, degrees R.

T_g = temperature of the gas, degrees R.

T_W = temperature of the walls, degrees R.

Thus the heat received (or lost) by the thermocouple by convection is equal to the heat lost (or gained) from the thermocouple by radiation at its equilibrium temperature, or

$$CeA_1(T_t^4 - T_W^4) = h_c A_2 \ (T_g - T_t) \times 10^8$$

Now since radiation is proportional to the fourth power of the absolute temperature, the radiant heat transfer will be very great at high temperatures where the wall temperature is at all different from the gas temperature. Therefore, a thermocouple in a gas at 2500 F, located within walls at 2300 F will have a much greater relative error than a gas at 700 F located in a flue at 500 F., for the same temperature difference of 200 degrees. Where the thermocouple is located in gases at, say, 2000 F, adjacent to cold boiler tubes at 350 F, the measurement may be very much in error.

The presence of radiating gases and glowing carbon particles, as in the firing of pulverized coal, complicates mathematical considerations, since these substances will also radiate to the thermocouple to an extent governed by their volume and their concentration. The presence of these heat radiators which are also absorbers will ordinarily decrease the indicated error, however.

The foregoing facts are well known by most engineers, and also are many of the means of eliminating errors. For example, it is possible to cover the hot junction with a material having a low emissivity, which while not affecting the convection heat transfer from the gas to the sensitive element, does decrease the radiation to other surfaces. It is also possible to put shields around the hot junction so it cannot "see" the colder surfaces; to use a small diameter thermocouple, or a number of thermocouples of different size, so as to extrapolate readings down to one of "zero" or optimum size; to use a bare thermocouple with calculated corrections using empirical formulas, and so on. Most of these devices can be readily understood by an examination of the equations shown above.

A thermocouple which will probably give the best readings in a test installation, such as that used at the Boiler Lab, is one of the high velocity type. Here the flow of gases over that hot junction of the thermocouple is forced by means of an aspirator pump. This increases the convection heat transfer to the thermocouple, thereby causing it to read more correctly. According to the theory of the high velocity thermocouple, the reading with no suction (with no gas flow past the thermocouple junction) will be considerably in error because of the poor convection heat transfer from the gases to the Thermocouple. As the suction (and gas flow) is increased, the temperature indicated rises, until a value is reached where the convection heat transfer from the gases to the thermocouple is so great that the heat losses of the instrument by conduction and radiation are relatively negligible. A further increase in gas flow results in no appreciable temperature rise thus showing that the true temperature has been reached. If a metal tube construction is used, this form of a high velocity thermocouple does not give the true temperature, it might be added. The best shield is a number of small refractory tubes around the hot junction.

From a discussion of thermocouples in general, the next step is to examine those used to obtain data at the Boiler Lab. The thermocouples used for measurement of gas temperature throughout the furnace and in the stacks of boilers under test there are of the unshielded junction type. Eight of them are used in the stacks in each test to determine the gas temperature, in which we are primarily interested in the study of boiler efficiencies. The thermocouples are placed just below the gas sampling tubes, which have inverted cups on the end, thereby giving a "cupping" action, which aids in the more accurate measurement of temperatures.

The exposed couples are made of iron-constantan, and in some cases, of nichrome constantan.

As has been said, the use of unshielded junctions can lead to considerable error because of radiation effects. In this particular installation, the thermocouple junctions are directly above the economizers, which are almost without exception equipped with large fins on the tubes to take full advantage of radiation and convection. Therefore, where these effects are desirable and necessary as far as heat transfer to the economizers are concerned, they have a most undesirable effect on the thermocouples.

This fact is, of course, recognized by the engineers of the Laboratory, and attempts at corrections are made in the following manner. Thermocouples are also installed just before the economizers, and continuous readings made on them in conjunction with the readings being taken above the economizers. Knowing the volume and weight of gases passing through the economizers, their approximate specific heat, and their indicated temperature at two points, and also the mass of water passing through the economizer and the temperature at inlet and exit, a heat balance is obtained, which will indicate the amount and direction of the observed thermocouple readings. This procedure is technically correct, of course, and with accurate data should give good results. As seen above, though, much of the data could conceivably be in error, such as the specific heat of the gases, and their actual mass rate of flow. Also, the temperature measurements of the gases at both locations are being made with instruments which are known to likely be in error.

Therefore, in order to avoid these calculations, and at the same time to be sure of the accuracy of temperature measurements the installation of thermocouples capable of good precision is recommended. By dividing the stack into nine rectangles of equal area, and installing the couple in the middle of each rectangle as suggested for the Orsat sampling tubes, a series of temperature readings could be obtained, which, when averaged, should give very representative results of actual conditions.

The error which is occasioned by incorrect thermocouple readings will be of the following magnitude, in general, recalling that the method of calculation of this loss is multiplication of the specific heat of the gases time the weight of dry flue gases per pound of fuel times the difference in the stack gas temperature and the lowest theoretical stack temperature. As can be seen, the specific heat of the gases will be in the neighborhood of 0.24; the weight of dry gases per pound of fuel, except at very low loads, in the vicinity of fifteen to twenty pounds, leaving the temperature difference as the only factor to vary appreciably. Assuming the actual stack temperature at a high rate of steaming to be $600^{\circ}F$, a bare thermocouple may be in error as much as 35°. Thus, the approximate error would become (0.24)(16.0)(35), or 134 BTU per pound of oil. Using 18,500 BTU oil as a basis of comparison, this is 0.725% error. As can be seen at lower rates of steaming, where exit gas temperature will not be as high as 600°, the bare thermocouple will not be in as much error, and at very low steaming rates, this error is probably inconsequential. But in view of the fact that tests are made at all steaming rates, including overloads, and also that thermocouples are installed throughout hotter parts of the furnace to obtain vital information, the installation of a different type thermocouple should be made.

Another measurement problem and one that is receiving much attention from the instrument department of the Boiler Lab, is that of determining accurately the temperature of superheated and saturated steam. At present, liquid-in-glass thermometers are used in the lines. When readings are made during the test, the identifying number of the thermometer is entered with the readings, enabling personnel in the calculating room to correct the reading, with the aid of a calibration chart of the particular instrument. These calibration or correction charts are prepared in the Instrument Laboratory, and one difficulty that is encountered is this; the thermometers are bought on contract by the Navy, and a certain depth well or immersion is specified. It is not always possible in the actual test set-up to mount the thermometers in the same type well for which they were designed. Insulation of the stem above the well will help, in case the well is not deep enough, but type, thickness, and height of insulation all affect the indicated temperature.

Many of the problems connected with liquid-in-glass thermometers could be made to disappear if, for the measurement of steam temperatures, resistance thermometers were used. The resistor element is of platinum wire, and the equipment is much more expensive than the liquid-in-glass type. However, if given proper care, their lifetime is great, and the accuracy of temperature measurements with this equipment is very high. I believe that a shift from liquid-in-glass thermometers for measurement of high temperature steams will be made at the Boiler Laboratory in the near future, and quite likely, the shift will be made to resistance thermometers.

CHAPTER X

HEATING VALUE OF FUELS

The heating value of fuel oil is determined by means of a calorimeter, of which there are two general types. The closed bomb type is the most popular and is generally regarded as being capable of greater precision, particularly when measuring heat values of solids and liquids. Here, a measured mass of fuel is caused to burn in an atmosphere of oxygen under pressures in the nature of 200 psi. As the bomb is sealed, the fuel burns without volume change. The energy released as a result of the combustion is transferred to a water bath, and is measured from data on the mass, temperature change, and specific heat of the water and the bomb.

The energy change is expressed by the equation $-Q_v = E_1 - E_2$ where E_1 and E_2 represent the internal energy of the original unburned fuel, and of the final products.

The second type, or constant pressure calorimeter, consists of a burner designed for liquid or gaseous fuels, to which a measured supply of fuel is delivered along with air, and a system of tubes, around which is circulated water and through which the combustion products pass. Heat is delivered through the tubes to the water, and the rate of water flow, the amount of tube surface, and the rate of combustion are such that the products are normally recooled to approximately the air supply temperature. Thus the energy released by the fuel can be determined from data on the temperature rise and the rate of flow of water.

Here the energy equation representing the process is $-Q_p = h_1 - h_2$ where h_1 and h_2 represent the enthalpies of the original unburned fuel and of the final products, respectively. These enthalpies are expressed per unit mass of fuel.

Heating values obtained by the use of the constant volume bomb calorimeter are known as "Higher Heating Values", hereafter referred to as H.H.V. When the bomb and its contained combustion products are cooled to normal room temperature, all the vapor inside will have condensed, giving up its latent heat to the surrounding water. It can be seen, therefore, that in this calorimeter, the H.H.V. can be obtained directly.

Unfortunately, this is not possible in the constant pressure type. The word "unfortunately" is used because in most combustion conditions, including that in a boiler furnace, the constant pressure and steady flow conditions of the calorimeter more nearly represent the actual conditions in the furnace. Because of the incompleteness, and the variation in completeness, of the vapor condensation in the constant pressure type, neither a true higher value, nor a constant function of that value is obtained, but an "apparent" higher value, which in most cases is several hundred BTU per pound below the true value.

With an understanding of the meaning of "heating values", it will be well to see just how they are used in the Long Form. From the basic definition of boiler efficiency, it is seen that these values are necessary, in that the heat content of the fuel is the measuring stick in determining just what percentage is converted to useful steam. In the Long Form the H.H.V. is used as the basis.

This is a point that is in dispute among many engineers. Until recently, engineers in this country favored using the H.H.V., arguing that the heat of condensation of the water vapor present is technically obtainable, and so is properly chargeable to the input account of the boiler. Engineers in Europe have for many years used the L.H.V., and more and more people in this country are coming around to this opinion. I believe that it is the more suitable. In the design of a boiler, it is known beforehand that the heat of condensation is not going to be obtainable, for the dew point of the products of combustion is in the vicinity of 125 F., and the temperature of the gases of combustion is much higher. In fact, designers do not want these BTU's, for moisture in a boiler can mean corrosion by sulphuric acid. Knowing that this heat is never going to appear in a pound of fuel, it seems reasonable not to charge the boiler for it.

It has been seen that the L.H.V. cannot be obtained directly. There are means of getting it, however if the H.H.V. is known, and this is a simple laboratory procedure. The following equation is applicable:

$$L.H.V. = H.H.V. - 1050 \times \frac{18.02}{2.02} \times f = H.H.V. - 9450f$$

where f is the fraction of hydrogen in the fuel, lbs./lb.

Under ordinary conditions this expression is sufficiently exact.

The results below, plotted in figure 3, indicate what apparent efficiency changes will occur, using the above equation to adjust the H.H.V. to L.H.V. They will also indicate why European boilers, at first glance, will appear to be more efficient than ours.

RUN	PERCENT POWER	H.H.V.	L.H.V. by formula	OVERALL EFF. by LHV	by HHV
Min. S.H	5.0	18645	17600	85.85	81.36
A	16.9	18647	17602	92.25	87.41
B	24.4	18647	17602	92.90	88.06
C	44.3	18640	17595	92.70	87.73
D	47.6	18638	17593	92.30	87.39
E	70.4	18644	17599	90.40	85.70
F	78.3	18641	17596	90.25	85.57
G	99.5	18648	17609	88.50	83.94
Overload	119.0	18634	17589	87.30	82.72

Item 20B in the Long Form is titled "Increase in Heat Value At Constant Pressure over that at Constant Volume", and is given as 25 BTU per pound. This is a minor item, but in the interest of the best possible accuracy and refinement, should be correct. 25 BTU is probably a good figure for the heavier fuels of many years ago, but does not seem to be correct for the lighter fuels that the Navy uses today.

Chemical formula of the ordinary grade of Navy Special Fuel Oil is C_8H_{16}. When it burns, the following reactions takes place:

$$C_8H_{16} + 12\ O_2 \longrightarrow 8CO_2 + 8\ H_2O$$

It can be seen that there has been a contraction of four volumes of gas; the molecular weight of the fuel being 112, the equivalent of the work done at 100 F is

$$\frac{4 \times (1545)\quad(560)}{(112)\quad(778)} = 39.8 \text{ BTU.}$$

A change in Item 20B from 25 BTU to 40 BTU is therefore suggested.

CHAPTER XI

A.S.M.E. POWER TEST CODE

A comparison between the A.S.M.E. Power Test Code and the Long Form is interesting. The aim of each is the same, and this aim is accomplished in a slightly different manner.

One of the first statements of the Code is an estimate of the accuracy likely to be attained in the analysis of a boiler. As is stated, there is no possible basis upon which to determine the probable limits of error, but the Power Test Code Committee feels that the limits of accuracy reasonably be taken to be within 3%. Sources of error are listed as sampling of the fuel, and the difficulty of determining whether samples collected for determination of moisture in the steam, and for gas analyses, are representative of the bulk. The Committee feels that while heat balances are often reported to the nearest BTU, and to the nearest 1/100 of 1%, the present state of the art does not provide means for attaining such accuracy.

It is true that the practice of taking balances out to the second decimal place is fruitless. However, the difficulty of sampling oil is not nearly so difficult as sampling coal, and with present Naval boilers, the quality of the steam leaving the drum is almost without exception 100%. Therefore it can be seen, that while necessarily the A.S.M.E. has formulated a code that will work equally as well with all types of boilers, if it is used with Naval boilers under test at a well-equipped laboratory much better results will be obtained than it is predicted are possible. It then follows that the best method of getting boiler efficiencies will be to use a specialized form suiting the characteristics of the boiler under test. This the Naval Boiler Laboratory feels they have.

Going into a more detailed comparison between the two methods, it is seen that many of the requirements are the same. The A.S.M.E. Code specifies a test of four hours duration, as does the Long Form, with a warm-up period of at least three hours before the test is begun. The instruments and apparatus required for the test are the same, such as scales for fuel and water, similar thermometers and thermocouples, calorimeters, meters, gas sampling and analyzing apparatus. Intervals of recording of measurements are to be short enough to give good averages.

In the Power Test Code, the initial recordings are those of a general nature, such as date of test, type of boiler and make, the conductor of the test, and the object. A description of the boiler is entered in the spaces following, including the amount of surface, the volume of the furnace, the number of burners, and the pertinent dimensions. These items are paralleled by the heading "General Data" on the Long Form. Next, in the Code, appears the analysis of the fuel, as it does on the Long Form, and then the gas analysis. Similarly, next are recorded the pressures, drafts, and temperatures throughout the unit.

Many of the items under "Primary Calculations" in the Long Form appear under "Hourly Quantities", and"Unit Quantities" in the Code. The latter are not nearly so complete, however, although they do include the vital heat absorption rates of all units. Such items as equivalent evaporation of the saturated and superheated sides, and the economizers are not included.

The heat absorption rates of all the units, mentioned above, are totaled to give a "rate of heat absorption per pound of fuel, (as fired)", and the next item recomputes this on a dry fuel basis, which is not done in the Long Form. It would be well to make some similar correction in the Long Form, as pointed out previously. The next step in the Code is to obtain the actual efficiency, by dividing the recomputed heat absorption rate, per pound of fuel, by the heat content of the fuel. No attempt is made to correct the heat content of the fuel by increases in its heat value at constant pressure over that at constant volume, or by the increase due to the difference in the fuel temperature and the incoming air temperature. Also, no attempt is made to obtain the various efficiencies of the component parts of the boiler, as is done in the Long Form, the efficiency of the steam-generating unit as a whole being the only one calculated.

The latter part of the Power test Code is the Heat Balance, where the heat losses, and the heat absorbed by the boiler, are balanced against the heating value of the fuel. The heat losses included are those incurred from moisture in the fuel, from water from combustion of hydrogen, from moisture in the air, to the dry chimney gases, the incomplete combustion of carbon, and to that which is unaccounted for. The concept of lowest theoretical stack temperature is not used, nor is the total air supplied broken down into the theoretical required and the excess.

Many of the computations are made by the same equations in both of the methods, and some differ in a small degree. 0.24 is used for the specific heat of the gases of combustion in the Power Test Code, while 0.25 is used in the Long Form. The equation used to compute the heat loss from the hydrogen in the fuel is, by the Long Form, 1089 +

0.46 (difference in temperature of entering air and exit gases) x weight of the moisture from burning hydrogen. The A.S.M.E. form uses the expression 1090.7 + 0.455 x Temperature of the gases leaving the economizer - temperature of the fuel, all multiplied by 9 times the percentage of hydrogen in the fuel. This will mean a difference of a few BTU's.

The A.S.M.E. equation for the moisture in the steam is given as H - 1150.4 - 0.47 x (Temp. of gases leaving the economizer -212), all divided by the latent heat in the steam at the pressure in the steam main. H is the total heat of the saturated steam at the boiler outlet pressure. The Long Form equation is

$$1 - \frac{0.475\ (\text{T} - \text{Avg. Calorimeter Temp.})}{\text{Latent Heat}}$$

Both of these equations are empirical, and it has been shown that the use of the Mollier chart is a more satisfactory means of getting the moisture in the steam.

The specific heat for moisture is taken as 0.46 in the Long Form, and as 0.47 in the Power Test Code. It is likely that in any given test installation 0.46 is the better value, but greater accuracy can be achieved in an easy manner by use of the steam tables.

In brief, the Long Form and the A.S.M.E. code both aim at the same target, the calculation of boiler efficiency. The Long Form is more specialized and more complete, and serves the purpose of the Navy far better than the A.S.M.E. code does, for it permits close scrutiny of the boiler as a whole, and at all component parts. The best points and the shortcomings of any unit are readily apparent when compared against a standard, or another boiler under test. As far as the A.S.M.E. code goes, it will produce almost as accurate results as the Long Form under many test conditions. But for use at the Naval Boiler and Turbine Laboratory, where facilities are available for very accurate work, it is definitely inferior to the Long Form.

CHAPTER XII

CONCLUSIONS

The Long Form can be regarded as a valuable tool of the Naval Service, for by its use the true performance of the boiler, the heart of the Engineering installation of our ships, can be accurately judged. It assures the Navy that it is getting the best product that is available from the many manufacturers of the country.

The Long Form is not regarded as an infallible, nor as a static, instrument. It has been in use for many years, and has been revised many times. Changes must be made to accomodate new types of boilers and when new instruments and methods come to the front, if it is to do the job in the future that it has done so well in the past.

The last revision of the Form was made in 1940, and it appears that the changes made at that time furthered its superiority over other methods of calculation of boiler efficiency. It is a specialized, thorough, and complete analysis. It is hoped that the suggestions made here will enable even better results to be attained by its use.

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NAVAL BOILER LABORATORY, NAVY YARD, PHILADELPHIA, PA.
BOILER TEST — LONG WORK FORM — SHEET No. 1

Test No. .... *Calculated by* .... *Time* .... *Date* .... *Run No.* ....

Item No.	ITEM		FORMULA	
	GENERAL DATA			
1	Generating Heating Surface	Sq.Ft.		
2	Superheater Heating Surface	Sq.Ft.		
3	Economizer Heating Surface	Sq.Ft.		
4	Total Boiler Heating Surface	Sq.Ft.	Item 1 + Item 2 + Item 3	
5	Air Heater Heating Surface	Sq.Ft.		
6	Total Furnace Volume	Cu.Ft.	Sat. S.H.	
7	Type of Registers			
8	Opening of Register Doors		Sat. S.H.	
9	Position of Burner Barrels	In.	Sat. S.H.	
10	Type of Sprayers			
11	Number and Size of Sprayers		Sat. S.H.	
12	Burners in Use		Sat. S.H.	
12A	Full Power Equiv. Evap.	Lbs./Hr.		
	FUEL PARTICULARS			
13	N.B.L. Number of Oil			
14	Carbon	Percent		
15	Hydrogen	Percent		
16	Sulphur	Percent		
17	Nitrogen	Percent		
18	Oxygen and Undetermined	Percent		
19	Free Moisture	Weight Percent		
20	Heat Value by Calorimeter	BTU/Lb.		
20A	Increase in Heat Value at Fuel Temp. over that at Temp. of Air at Boiler Casing Inlet	BTU/Lb.	0.46(Item 52 — Item 50)	
20B	Increase in Heat Value at Constant Press. over that at Constant Volume	BTU/Lb.	$\Delta H_p - \Delta H_v = 25$	25
20C	Total Sensible Heat	BTU/Lb.	Item 20 + Item 20A + Item 20B	
	SUMMARIZED TEST DATA			
21	Avg. Carbon Dioxide	Percent CO_2	Sat. S.H.	
22	Avg. Oxygen	Percent O_2	Sat. S.H.	
23	Avg. Carbon Monoxide	Percent CO	Sat. S.H.	
24	Avg. Nitrogen	Percent N_2	Sat. S.H.	

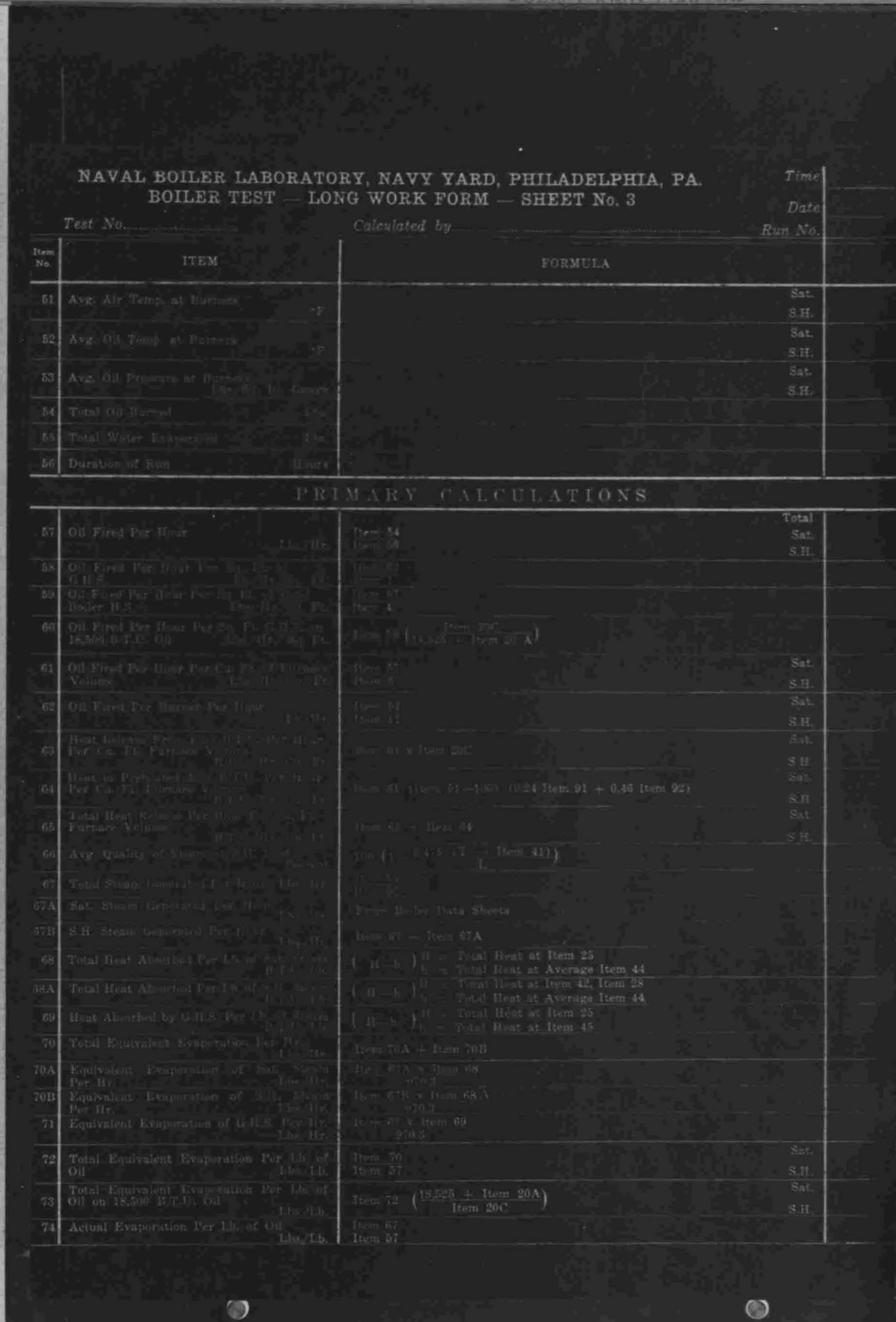
Figure 1

NAVAL BOILER LABORATORY, NAVY YARD, PHILADELPHIA, PA.
BOILER TEST — LONG WORK FORM — SHEET No. 2

Time
Date
Test No. .... *Calculated by* .... *Run No.*

Item No.	ITEM	FORMULA	
25	Avg. Steam Drum Press. Lbs./Sq. In. Abs.		
26	Avg. Steam Drum Outlet Press. Lbs./Sq. In. Abs.		
27	Avg. S. H. Inlet Pressure Lbs./Sq. In. Abs.		
28	Avg. S. H. Outlet Pressure Lbs./Sq. In. Abs.		
29	Avg. Press. Before Main Stop Lbs./Sq. In. Abs.		
30	Avg. Press. After Main Stop Lbs./Sq. In. Abs.		
30A	Avg. Water Press. Before Econ. Lbs./Sq. In. Abs.		Sat. S.H.
30B	Avg. Water Press. After Econ. Lbs./Sq. In. Abs.		Sat. S.H.
31	Avg. Atmospheric Press. Ins. Hg		
32	Avg. Air Pressure at Boiler Casing Inlet Ins. Water		Sat. S.H.
33	Avg. Air Pressure at Burners Ins. Water		Sat. S.H.
34	Avg. Pressure in Furnace Ins. Water		Sat. S.H.
35	Avg. Flue Gas Pressure Before Superheater Ins. Water		
36	Avg. Flue Gas Pressure After Superheater Ins. Water		
37	Avg. Flue Gas Pressure Before Econ. or Air Heater Ins. Water		Sat. S.H.
38	Avg. Flue Gas Pressure After Econ. or Air Heater Ins. Water		Sat. S.H.
39	Avg. Pressure in Breeching Ins. Water		Sat. S.H.
40	Avg. Pressure at Base of Stack Ins. Water		Sat. S.H.
41	Avg. Calorimeter Temperature °F.		
42	Avg. Steam Temp. at S.H. Outlet °F.		
43	Avg. Steam Temp. After Main Stop °F.		
44	Avg. Temp. Feed Water at Feed Stop °F.		Sat. S.H.
45	Avg. Temp. Feed Water Leaving Econ. °F.		Sat. S.H.
46	Avg. Temp. Gases Leaving C.H.S. °F.		Sat. S.H.
47	Avg. Temp. Gases Leaving Boiler °F.		Sat. S.H.
48	Avg. Dry Bulb Temp. °F.		
49	Avg. Wet Bulb Temp. °F.		
50	Avg. Temp. of Air Entering Boiler Casing Inlet °F.		Sat. S.H.
50A	Avg. Air Temp. After Air Heater °F.		Sat. S.H.

Figure 1



NAVAL BOILER LABORATORY, NAVY YARD, PHILADELPHIA, PA.
BOILER TEST — LONG WORK FORM — SHEET No. 3

Test No. .... Calculated by .... Time / Date / Run No.

Item No.	ITEM	FORMULA	
51	Avg. Air Temp. at Burners °F		Sat. / S.H.
52	Avg. Oil Temp. at Burners °F		Sat. / S.H.
53	Avg. Oil Pressure at Burners Lbs. Sq. In. Gauge		Sat. / S.H.
54	Total Oil Burned Lbs.		
55	Total Water Evaporated Lbs.		
56	Duration of Run Hours		
	PRIMARY CALCULATIONS		
57	Oil Fired Per Hour Lbs./Hr.	Item 54 / Item 56	Total / Sat. / S.H.
58	Oil Fired Per Hour Per Sq. Ft. G.H.S. Lbs./Hr./Sq. Ft.	[illegible]	
59	Oil Fired Per Hour Per Sq. Ft. of Boiler H.S. Lbs./Hr./Sq. Ft.	Item 57 / Item 4	
60	Oil Fired Per Hour Per Sq. Ft. G.H.S. on 18,500 B.T.U. Oil Lbs./Hr./Sq. Ft.	Item 58 (Item 20C / (18,525 + Item 20 A))	
61	Oil Fired Per Hour Per Cu. Ft. of Furnace Volume Lbs./Hr./Cu. Ft.	Item 57 / Item 6	Sat. / S.H.
62	Oil Fired Per Burner Per Hour Lbs./Hr.	Item 57 / Item 11	Sat. / S.H.
63	Heat Release From Oil B.T.U. Per Hour Per Cu. Ft. Furnace Volume B.T.U./Hr./Cu. Ft.	Item 61 x Item 20C	Sat. / S.H.
64	Heat in Preheated Air B.T.U. Per Hour Per Cu. Ft. Furnace Volume B.T.U./Hr./Cu. Ft.	Item 61 (Item 51 − 100) (0.24 Item 91 + 0.46 Item 92)	Sat. / S.H.
65	Total Heat Release Per Hour Per Cu. Ft. Furnace Volume B.T.U./Hr./Cu. Ft.	Item 63 + Item 64	Sat. / S.H.
66	Avg. Quality of Steam at Sat. Outlet Percent	100 (1 − 0.475 (T − Item 41) / L)	
67	Total Steam Generated Per Hour Lbs./Hr.	Item 55 / Item 56	
67A	Sat. Steam Generated Per Hour Lbs./Hr.	From Boiler Data Sheets	
67B	S.H. Steam Generated Per Hour Lbs./Hr.	Item 67 − Item 67A	
68	Total Heat Absorbed Per Lb. of Sat. Steam B.T.U./Lb.	(H − h) H = Total Heat at Item 25; h = Total Heat at Average Item 44	
68A	Total Heat Absorbed Per Lb. of S.H. Steam B.T.U./Lb.	(H − h) H = Total Heat at Item 42, Item 28; h = Total Heat at Average Item 44	
69	Heat Absorbed by G.H.S. Per Lb. of Steam B.T.U./Lb.	(H − h) H = Total Heat at Item 25; h = Total Heat at Item 45	
70	Total Equivalent Evaporation Per Hr. Lbs./Hr.	Item 70A + Item 70B	
70A	Equivalent Evaporation of Sat. Steam Per Hr. Lbs./Hr.	Item 67A x Item 68 / 970.3	
70B	Equivalent Evaporation of S.H. Steam Per Hr. Lbs./Hr.	Item 67B x Item 68A / 970.3	
71	Equivalent Evaporation of G.H.S. Per Hr. Lbs./Hr.	Item 67 x Item 69 / 970.3	
72	Total Equivalent Evaporation Per Lb. of Oil Lbs./Lb.	Item 70 / Item 57	Sat. / S.H.
73	Total Equivalent Evaporation Per Lb. of Oil on 18,500 B.T.U. Oil Lbs./Lb.	Item 72 ((18,525 + Item 20A) / Item 20C)	Sat. / S.H.
74	Actual Evaporation Per Lb. of Oil Lbs./Lb.	Item 67 / Item 57	

Figure 1

NAVAL BOILER LABORATORY, NAVY YARD, PHILADELPHIA, PA.
BOILER TEST — LONG WORK FORM — SHEET No. 4

Time

Date

Test No................... *Calculated by*.................................... *Run No.*

Item No.	ITEM	FORMULA	
75	Boiler Horse Power H.P.	$\frac{\text{Item 70}}{34.5}$	
76	Percent of Full Power Percent	$100\left(\frac{\text{Item 70}}{\text{Item 12A}}\right)$	
77	B.T.U. Fired Per Hour Per Sq. Ft. G.H.S. B.T.U./Hr./Sq.Ft.	Item 58 x Item 20C	
77A	Item 77 Based on 18,500 B.T.U. Oil	Item 58 (18,825 ÷ Item 20A)	
78	Equivalent Evaporation Per Hour Per Sq. Ft. of Total Boiler H.S. Lbs./Hr./Sq.Ft.	$\frac{\text{Item 70}}{\text{Item 4}}$	
79	B.T.U. Absorbed by Total Boiler H.S. Per Hr. Per Sq. Ft. B.T.U./Hr./Sq.Ft.	Item 78 x 970.3	
80	Actual Evaporation Per Hour Per Sq. Ft. G.H.S. Lbs./Hr./Sq.Ft.	$\frac{\text{Item 67}}{\text{Item 1}}$	
81	Saturated Steam Temp. at S.H. Outlet Press. °F.	From Item 28 and Steam Tables	
82	Superheat at S.H. Outlet °F.	Item 42 — Item 81	
	COMBUSTION CALCULATIONS		
83	Relative Humidity Percent	From Psychrometric Tables Using Items 48 & 49	
84	Moisture in Air Lbs./Cu.Ft.	From Psychrometric Tables Using Items 48 & 49	
85	Dew Point °F.	From Psychrometric Tables Using Items 48 & 49	
86	Vapor Pressure Ins. Hg.	From Psychrometric Tables Using Item 85	
87	Weight of Dry Air at Boiler Casing Inlet Lbs./Cu.Ft.	$1.32165\left(\frac{\text{Item 31} - \text{Item 86} + (\text{Item 32} \div 13.5)}{459.6 + \text{Item 48}}\right)$	
87A	Item 87 Based on 100° F. Air Temp., Relative Humidity 40% Lbs./Cu.Ft.	$1.32165\left(\frac{\text{Item 31} - 0.764 + (\text{Item 32} \div 13.5)}{559.6}\right)$	
88	Dry Air Theoretically Required for Combustion of 1 Lb. of Fuel Lbs./Lb.	$0.3449\left(\frac{C}{3} + H_2 + \frac{S - O_2}{8}\right)$	
89	Weight of Dry Gases Per Lb. of Fuel Lbs./Lb.	$\left(\frac{4\ CO_2 + O_2 + 700}{3\ (CO_2 + CO)}\right)\left(\frac{C + (S \div 1.835)}{100}\right)$	Sat. S.H.
90	Weight of Moisture from Burning Hydrogen Lbs./Lb.	Item 15 x 0.0894	
91	Weight of Dry Air Used Per Lb. of Fuel Lbs./Lb.	$\text{Item 89} + \text{Item 90} - \frac{(\text{Item 14} + \text{Item 15} + \text{Item 16})}{100}$	Sat. S.H.
92	Weight of Moisture in Air Per Lb. of Fuel Lbs./Lb.	$\frac{\text{Item 91} \times \text{Item 84}}{\text{Item 87}}$	Sat. S.H.
92A	Item 92 Based on 100° F. Air Temperature, Relative Humidity 40% Lbs./Lb.	$\frac{0.00114\ \text{Item 91}}{\text{Item 87A}}$	Sat. S.H.
93	Weight of Total Products of Combustion Per Lb. of Fuel Lbs./Lb.	Item 89 + Item 90 + Item 92	Sat. S.H.
94	Percentage Excess Air Percent	$100\left(\frac{\text{Item 91}}{\text{Item 88}} - 1\right)$	Sat. S.H.
95	C.F.M. Air Through Blowers Cu.Ft./Min.	$\frac{\text{Item 57}}{60} \times \frac{\text{Item 91}}{\text{Item 87}}$	Sat. S.H.
95A	Air Horsepower A.H.P.	Item 32 x Item 95 x 0.000156566	
96	Steam Used by Blowers Lbs./Hr.	From Blower Curves Using Item 95 and Item 32, or Using Item 95A.	
97	Percent Total Steam Used to Operate Blowers Percent	$100\left(\frac{\text{Item 96}}{\text{Item 70}}\right)$	
98	Pounds of Steam Used by Blowers per 1000 Cu.Ft. of Air Supplied Lbs.	$16.667\left(\frac{\text{Item 96}}{\text{Item 95}}\right)$	
99	Percent Total Steam Remaining After Deducting Blower Steam Percent	100 — Item 97	
100	Lowest Theoretical Stack Temperature °F.	a. Boiler with Air Heater — Item 50 b. Boiler with Economizer — Item 44 c. Boiler without Air Heater or Econ. — Sat. Temp. at Item 25	Sat. S.H.

Figure 1

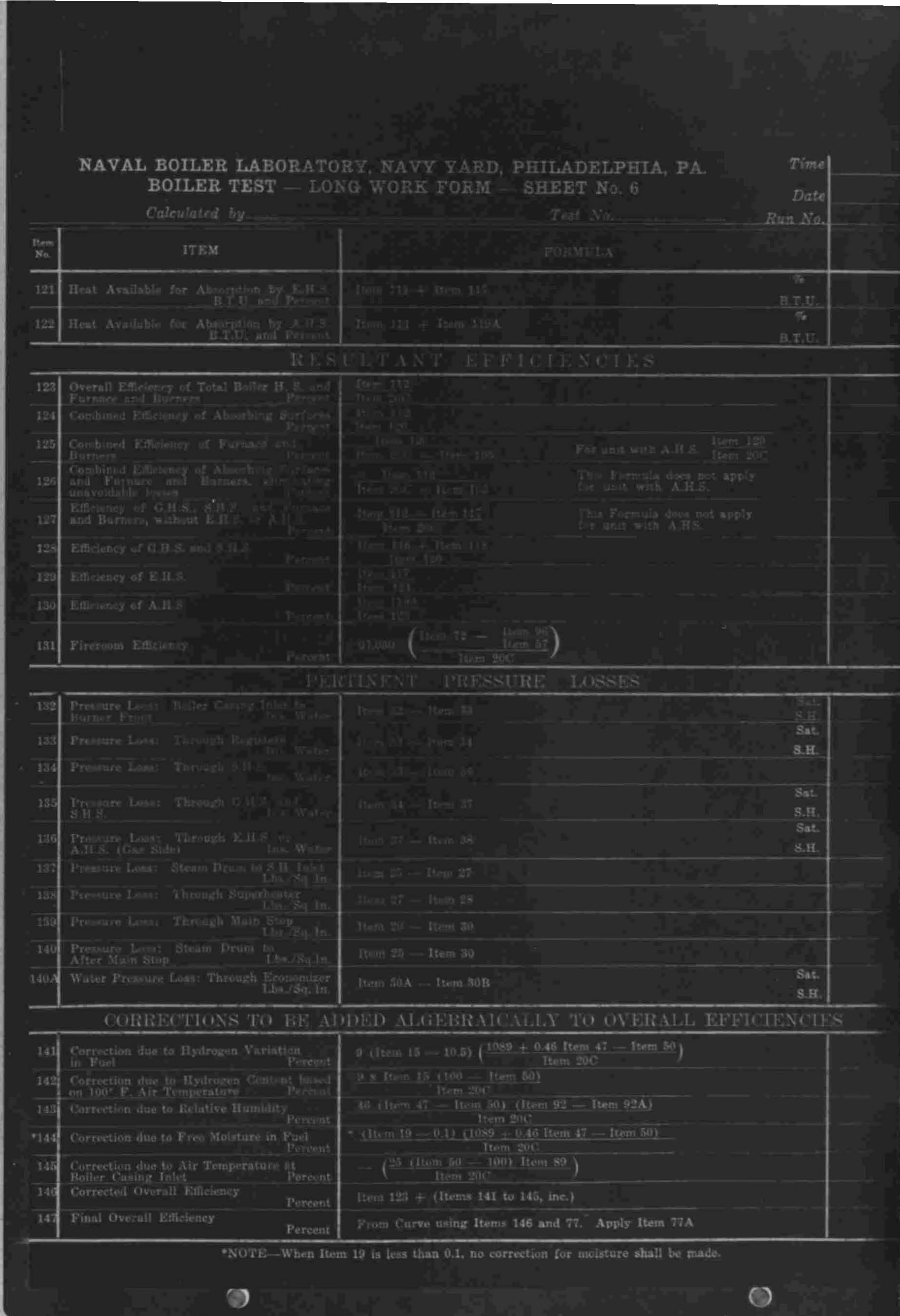
NAVAL BOILER LABORATORY, NAVY YARD, PHILADELPHIA, PA.
BOILER TEST — LONG WORK FORM — SHEET No. 5

Test No..................... *Calculated by*.................................... *Time* *Date* *Run No.*

Item No.	ITEM	FORMULA	
	HEAT BALANCE		
*101	Heat Loss: Moisture from H_2 in Fuel from Temp. Air Entering Boiler Casing to Lowest Theoretical Stack Temp. B.T.U. and Percent	(1089.0 + 0.46 Item 100 — Item 50) Item 90 (See Note)	% B.T.U.
*102	Heat Loss: Free Moisture in Fuel from Temp. Oil at Burners to Lowest Theoretical Stack Temp. B.T.U. and Percent	(1089.0 + 0.46 Item 100 — Item 52) $\frac{\text{Item 19}}{100}$ (See Note)	% B.T.U.
103	Heat Loss: Moisture in Theoretical Air from Temp. Air Entering Boiler Casing to Lowest Theoretical Stack Temp. B.T.U. and Percent	$\frac{\text{Item 92 x 0.46 (Item 100 — Item 50) Item 88}}{\text{Item 91}}$	% B.T.U.
104	Heat Loss: Theoretical Dry Flue Gases from Temp. Air Entering Boiler Casing to Lowest Theoretical Stack Temp. B.T.U. and Percent	0.25 (Item 100 — Item 50) (Item 88 + 1 — Item 90)	% B.T.U.
*105	Total Unavoidable Losses B.T.U. and Percent	Summation Items 101 to 104, inclusive (See Note)	% B.T.U.
106	Heat Loss: Incomplete Combustion of Carbon B.T.U. and Percent	10,160 $\left(\frac{CO}{CO_2 + CO}\right)\left(\frac{C}{100}\right)$	% B.T.U.
107	Heat Loss: Excess Air from Temp. Air Entering Boiler Casing to Lowest Theoretical Stack Temperature B.T.U. and Percent	0.24 (Item 100 — Item 50) (Item 91 — Item 88)	% B.T.U.
108	Heat Loss: Moisture Accompanying Excess Air from Temp. Air Entering Boiler Casing to Lowest Theor. Stack Temp. B.T.U. and Percent	$\frac{\text{Item 103 x Item 94}}{100}$	% B.T.U.
109	Heat Loss: Dry Flue Gases from Lowest Theoretical Stack Temp. to Temp. Gases Leaving Boiler B.T.U. and Percent	0.25 (Item 47 — Item 100) Item 89	% B.T.U.
110	Heat Loss: Moisture in Dry Flue Gases from Lowest Theoretical Stack Temp. to Temp. Gases Leaving Boiler B.T.U. and Percent	0.46 [illegible] (Item 47 — Item 100) (Item 90 + Item 92 + $\frac{\text{Item 19}}{100}$)	% B.T.U.
111	Heat Loss: Chargeable to all Absorbing Surfaces B.T.U. and Percent	Item 109 + Item 110 For Unit with A.H.S. Item 105 + Item 109 + Item 110	% B.T.U.
112	Heat Absorbed by Total Boiler Heating Surface B.T.U. and Percent	Item 74 $\left(\frac{\text{Item 68 x Item 67A + Item 68A x Item 67B}}{\text{Item 67}}\right)$	% B.T.U.
113	Heat Loss: Unconsumed H_2 and Hydrocarbons, Radiation, and unaccounted for B.T.U. and Percent	Item 200 — (Items 105 + 106 + 107 + 108 + 111 + 112) *Item 105 not to be included for Unit with A.H.S.	% B.T.U.
114	Heat Loss: Chargeable to Furnace and Burners B.T.U. and Percent	Items 106 + 107 + 108 + 113	% B.T.U.
115	Heat Loss: Chargeable to All Absorbing Surfaces and Furnace and Burners B.T.U. and Percent	Item 111 + Item 114	% B.T.U.
116	Heat Absorbed by G.H.S. Per Lb. of Fuel B.T.U. and Percent	Item 69 x Item 74	% B.T.U.
117	Heat Absorbed by E.H.S. Per Lb. of Fuel B.T.U. and Percent	Item 74 (h_1 — h) h_1 = Heat of Liquid at Item 45 h = Heat of Liquid at Item 44	% B.T.U.
118	Heat Absorbed by S.H.S. Per Lb. of Fuel B.T.U. and Percent	Item 112 — (Item 116 + Item 117)	% B.T.U.
119	Heat Absorbed by Air from Entrance to Fireroom to Boiler Casing Inlet Per Lb. of Fuel B.T.U. and Percent	(0.24 Item 91 + 0.46 Item 92) (Item 50 — Item 48)	% B.T.U.
119A	Heat absorbed by Air from Boiler Casing Inlet to Burners Per Lb. of Fuel B.T.U. and Percent	(0.24 Item 91 + 0.46 Item 92) (Item 51 — Item 50)	% B.T.U.
120	Heat Available for Absorption by Total Boiler Heating Surface B.T.U. and Percent	Item 111 + Item 112	% B.T.U.

*NOTE: For Unit with A.H.S., these losses are avoidable, since stack temperature may be same as inlet air temperature. These items are only to be used for inclusion in Total Heat Losses.

Figure 1



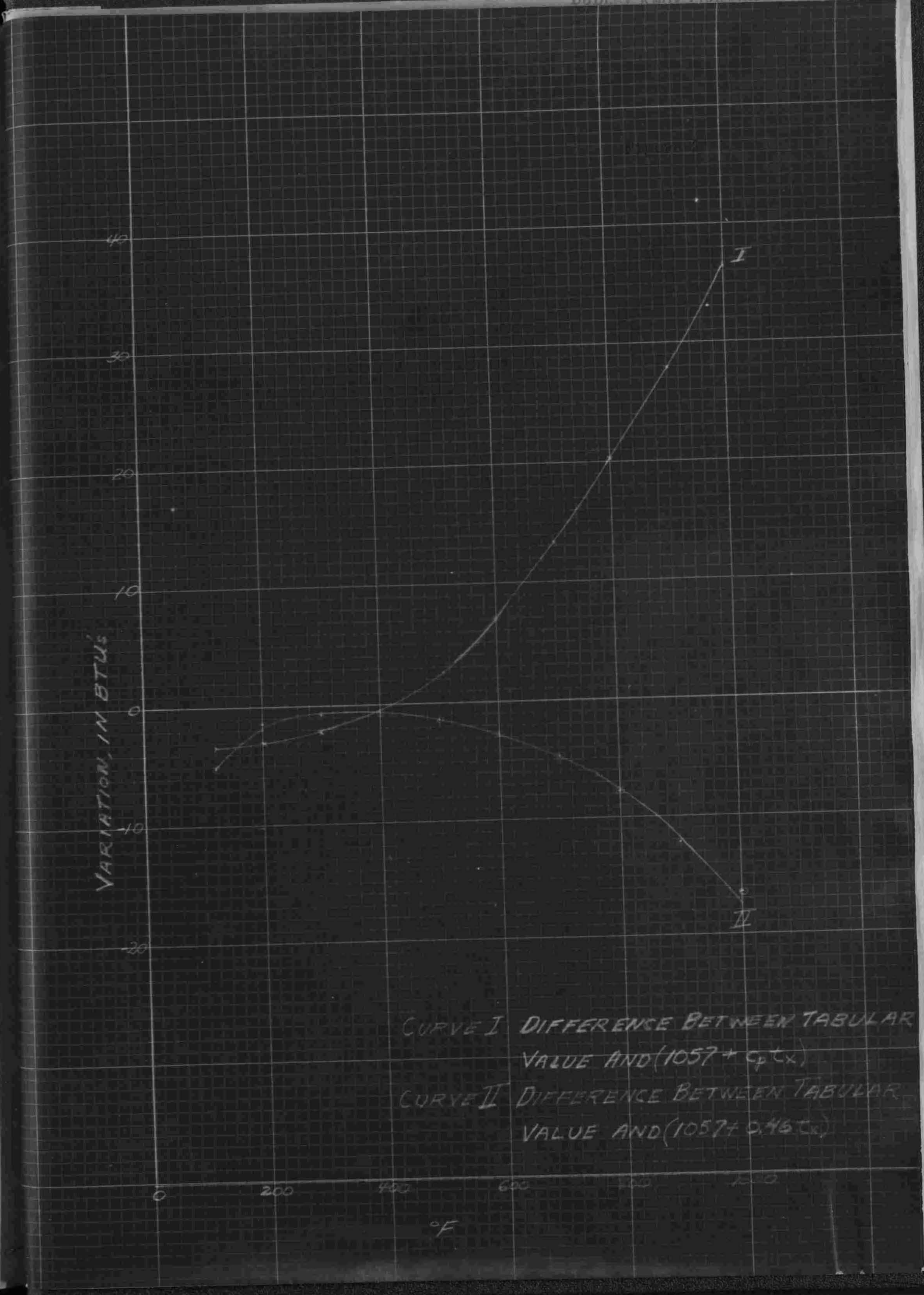
NAVAL BOILER LABORATORY, NAVY YARD, PHILADELPHIA, PA.
BOILER TEST — LONG WORK FORM — SHEET No. 6

Calculated by .... *Test No.* .... *Time* .... *Date* .... *Run No.* ....

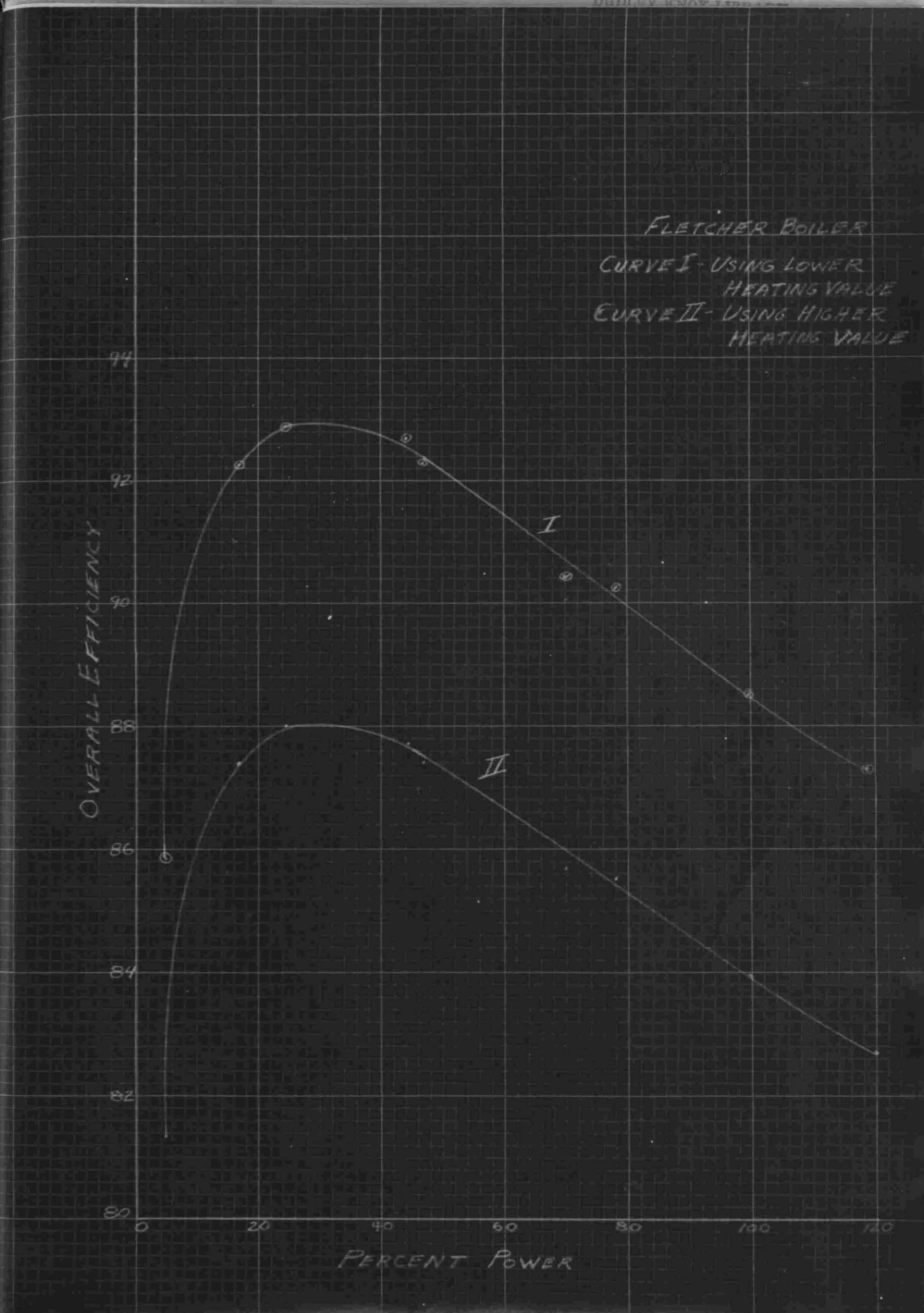
Item No.	ITEM	FORMULA	
121	Heat Available for Absorption by E.H.S. B.T.U. and Percent	Item 111 + Item 117	% B.T.U.
122	Heat Available for Absorption by A.H.S. B.T.U. and Percent	Item 111 + Item 119A	% B.T.U.
	RESULTANT EFFICIENCIES		
123	Overall Efficiency of Total Boiler H. S. and Furnace and Burners Percent	Item 112 / Item 20C	
124	Combined Efficiency of Absorbing Surfaces Percent	Item 112 / Item 120	
125	Combined Efficiency of Furnace and Burners Percent	Item 120 / (Item 20C — Item 105); For unit with A.H.S. Item 120 / Item 20C	
126	Combined Efficiency of Absorbing Surfaces and Furnace and Burners, eliminating unavoidable losses Percent	Item 113 / (Item 20C — Item [illegible]); This Formula does not apply for unit with A.H.S.	
127	Efficiency of G.H.S., S.H.S. and Furnace and Burners, without E.H.S. or A.H.S. Percent	(Item 112 — Item 117) / Item 20C; This Formula does not apply for unit with A.H.S.	
128	Efficiency of G.H.S. and S.H.S. Percent	(Item 116 + Item 118) / Item 120	
129	Efficiency of E.H.S. Percent	Item 117 / Item 121	
130	Efficiency of A.H.S. Percent	Item 119A / Item 122	
131	Fireroom Efficiency Percent	97,000 ((Item 72 — Item 96 / Item 57) / Item 20C)	
	PERTINENT PRESSURE LOSSES		
132	Pressure Loss: Boiler Casing Inlet to Burner Front Ins. Water	Item 32 — Item 33	Sat. S.H.
133	Pressure Loss: Through Registers Ins. Water	Item 33 — Item 34	Sat. S.H.
134	Pressure Loss: Through S.H.S. Ins. Water	Item [illegible] — Item 36	
135	Pressure Loss: Through G.H.S. and S.H.S. Ins. Water	Item 34 — Item 37	Sat. S.H.
136	Pressure Loss: Through E.H.S. or A.H.S. (Gas Side) Ins. Water	Item 37 — Item 38	Sat. S.H.
137	Pressure Loss: Steam Drum to S.H. Inlet Lbs./Sq. In.	Item 25 — Item 27	
138	Pressure Loss: Through Superheater Lbs./Sq. In.	Item 27 — Item 28	
139	Pressure Loss: Through Main Stop Lbs./Sq. In.	Item 29 — Item 30	
140	Pressure Loss: Steam Drum to After Main Stop Lbs./Sq. In.	Item 25 — Item 30	
140A	Water Pressure Loss: Through Economizer Lbs./Sq. In.	Item 30A — Item 30B	Sat. S.H.
	CORRECTIONS TO BE ADDED ALGEBRAICALLY TO OVERALL EFFICIENCIES		
141	Correction due to Hydrogen Variation in Fuel Percent	9 (Item 15 — 10.5) ((1089 + 0.46 Item 47 — Item 50) / Item 20C)	
142	Correction due to Hydrogen Content based on 100° F. Air Temperature Percent	9 x Item 15 (100 — Item 50) / Item 20C	
143	Correction due to Relative Humidity Percent	46 (Item 47 — Item 50) (Item 92 — Item 92A) / Item 20C	
*144	Correction due to Free Moisture in Fuel Percent	— (Item 19 — 0.1) (1089 + 0.46 Item 47 — Item 50) / Item 20C	
145	Correction due to Air Temperature at Boiler Casing Inlet Percent	— ((25 (Item 50 — 100) Item 89) / Item 20C)	
146	Corrected Overall Efficiency Percent	Item 123 + (Items 141 to 145, inc.)	
147	Final Overall Efficiency Percent	From Curve using Items 146 and 77. Apply Item 77A	

*NOTE—When Item 19 is less than 0.1, no correction for moisture shall be made.

Figure 1



40
30
20
10
0
-10
-20
VARIATION, IN BTU's
I
II
CURVE I DIFFERENCE BETWEEN TABULAR VALUE AND (1057 + $c_p t_x$)
CURVE II DIFFERENCE BETWEEN TABULAR VALUE AND (1057 + 0.46 t_x)
0
200
400
600
°F



FLETCHER BOILER
CURVE I - USING LOWER HEATING VALUE
CURVE II - USING HIGHER HEATING VALUE
OVERALL EFFICIENCY
PERCENT POWER
I
II
80
82
84
86
88
90
92
94
0
20
40
60
80
100
120